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THE ADAPTION OF CONTRAM TO THE MODELLING OF THE TEMPORAL DISTRIBUTION OF TRAFFIC DEMAND

BY

SHANE P.R. ALLAM

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering
University of Manitoba
Winnipeg, Manitoba

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ABSTRACT

It is known that departure time is an important consideration to commuters traveling to work in the morning, peak traffic hour. Predicting the nature of traffic flow in a road network depends not only upon the total demand but also upon the distribution of demand with time. Predicting this distribution, is dependent on accurately modelling commuter departure time selection, which in turn is dependent on the traffic conditions a commuter expects to encounter.

CONTRAM is a route assignment model which can handle traffic demand which is time varying. It works with an input distribution of demand with time, but this distribution is assumed fixed. This does not allow for the possibility that under different traffic conditions commuters may alter their departure times.

The goal of the research work described herein was to assess the adaptability of CONTRAM to the problem of determining the temporal distribution of traffic demand by combining it with a second model. The second model determined departure time selection as a function of the output of CONTRAM. The two worked iteratively together. The research moved from preliminary investigation using a single-origin destination pair to a more realistic network with multiple origins and destinations and multiple routes. The

resulting behavior of demand, and of traffic in the system were compared for a variety of changes to base networks.

Although some of the single origin-destination pair networks reached an equilibrium solution, demand for the multiple origin-destination problem never converged and showed variations within a band from iteration to iteration. Using comparisons of average demand distributions results showed that CONTRAM could be applied to this problem, and as it provided reasonable and logical results it could be used to compare alternative network plans for the multiple origin-destination problem. CONTRAM permits the modelling of a maximum of 13 time intervals. Therefore as the time frame of study increases a coarser approximation of continuous demand will result, and will limit the application.

ACKNOWLEDGEMENTS

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1.0 - INTRODUCTION

1.1 The Problem

The problem of congestion on urban roads is well known to any urban commuter traveling by road vehicle, especially those traveling to and from work. Historically traffic demand has been assumed to be uniformly distributed throughout periods of peak demand. This can be adequate for broad planning purposes.

It is known, however, that in reality traffic demand during peak periods is time dependent as commuters choose departure times based on desired times of arrival at their destination and expected traffic conditions. Vickery (1969) stated, ".there is a tendency for earlier arriving vehicles to encounter large delay and levels of congestion and for later arriving vehicles to avoid this congestion...". Empirical econometric models such as those developed by Small (1983), and Abkowitz (1980), have verified that departure time decisions, or work trip scheduling, are an important factor in the decision process of work trip commuters who must choose a time of departure based on desired times of arrival at work. Small concludes "..it is likely that many commuters...are currently traveling at other than their preferred times of day in order to avoid congestion." An increase in capacity may allow more people to shift the departure times to their preferred time. Without incorporating commuter departure time selection into the models of traffic flow such mechanisms will not be accounted for.

The collective departure time decisions of all commuters within a network results in the temporal distribution of demand for the network. It can be hypothesized reasonably that two networks with the same capacities and the same total demand can have very different resulting traffic conditions if the distributions of demand with time are very different.

When funds are readily available and there is room for expansion, problems with congestion can be solved by providing increased capacity, or more roads. As a city expands and/or operates under budget restraints, the ability to increase capacity is limited. It is therefore more important to understand clearly the nature of travel demand in the peak periods. With the goal of spreading demand over a greater time planners, engineers and economists have been looking to low cost traffic control measures such as the implementation of flexible work hours or staggered work hours. The need to predict the nature of traffic demand with time is enhanced even further as quantifying the effects of such plans hinges directly on the ability to predict the nature of commuter departure time decisions.

1.2 Research Direction

One of the problems in modelling choices of departure times has been the estimation of travel times for a network that has time varying demand. This has been done in a variety of ways for networks modelled as a single origin-destination pair. However, as discussed by Alfa (1986), extension of travel time estimation to realistic networks with time varying demand and in which travelers are free to choose their departure time has been limited.

CONTRAM is a route assignment model, developed by the Transportation Road Research Laboratory (Leonard et al. - 1978), which can handle time varying demand. However, CONTRAM works with an input temporal distribution of demand. It assumes that the distribution is fixed, regardless of the resulting traffic conditions. There is no flexibility in departure time choices once the distribution has been input into the model.

This thesis presents research to determine if CONTRAM can be extended to simulate commuters' choices of departure times. The research consisted of developing a working knowledge of CONTRAM and then adapting it to the problem of determining the temporal distribution of traffic demand. The latter is achieved by developing and incorporating a supplementary model to be used in conjunction with CONTRAM.

CONTRAM is used to estimate average speeds for each origin destination pair in each time interval for a given temporal distribution of traffic demand. The supplementary program can use this information to estimate travel times, evaluate users' costs, and then model commuter choice to redetermine the distribution of demand. The two can then be used iteratively together until a steady state is reached, if such a state exists.

This thesis first presents a review of models and research that consider vehicle flow characteristics under time varying demand and the dynamics of departure time selection. This includes a basic formulation of the problem. Secondly a description of the CONTRAM model is provided along with a description of some preliminary analysis that was performed on the CONTRAM model. A model is then formulated for use in conjunction with CONTRAM to predict departure time decisions. Adaption of the models to a simple single origin-destination pair is attempted. More complex networks are then studied using these models and various scenarios are examined. Throughout the analysis emphasis is on the incorporation of CONTRAM in the solution process.

2.0 - MODELLING TIME VARYING DEMAND - BACKGROUND

2.1 - Problem Formulation

To understand the nature of the problem of time-varying demand first consider the general behaviour of commuters in the morning making home-to-work trips. Individuals can leave at any time they choose. They have a desired arrival time at their destination, which is often assumed to be the work start time. Commuters incur different types of costs associated with their travel time: the cost of time spent on the road and costs associated with how their actual arrival time at work compares to the desired time of arrival. In the case of arriving early there is cost associated with idle time, while in the case of arriving late there may be lost productivity or docked wages. Commuters choose their time of departure to minimize their total cost. This requires some knowledge of existing or expected traffic conditions.

To establish the basic considerations in modelling time varying demand, consider a simple example of a single origin destination pair, A-D, connected by one link with a single bottleneck of fixed capacity, as shown in Figure 1. The bottleneck begins at B and ends at C. The problem for morning work trips is to solve for the vehicle departure rate from A as a function of time assuming a known, fixed total volume of travelers. In order to do this, it is necessary to be able to estimate the total travel time from A to D. This travel time consists of the free flow travel time from A to B (TAB) and from C to D (TCD) both of which are constant, and the time delayed at the bottleneck (TBC) which is dependent on the capacity and the nature of arrivals at the bottleneck as a function of time. The problem therefore consists of two distinct stages, estimating travel time under time varying demand and modelling departure time selection.

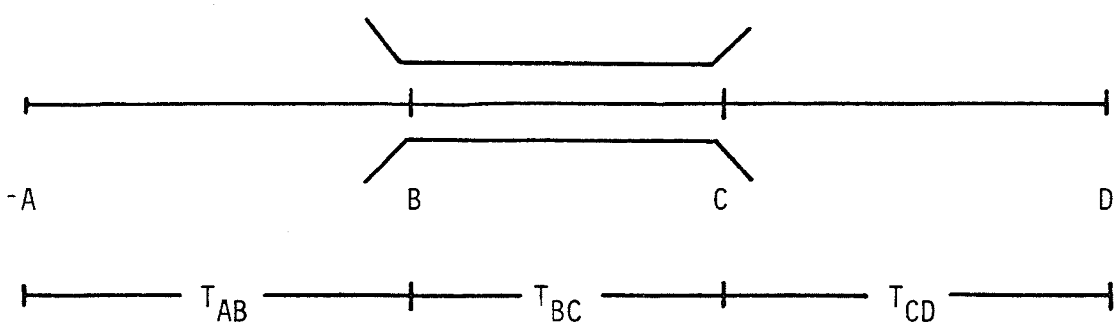


FIGURE 1 - BOTTLENECK

2.2 - Background Research

The problem of time varying demand in traffic systems has been considered and modelled in a variety of ways. Some researchers have considered the components of travel time estimation and departure rate from the origin as a function of time simultaneously, while others link the two in an iterative procedure that continues until equilibrium is reached. All use some form of cost model to determine the cost associated with the time of arrival upon which departure time decisions are made. A detailed review of models used for the temporal distribution of demand was given by Alfa (1986).

Many researchers have adapted the deterministic queuing models developed by Newell (1971) and May and Keller (1967) to the problem of time varying demand to solve for travel times. Fargier (1981) and Hendrickson and Kocur (1981) used deterministic queuing theory with a single work start time for all travelers and multiple work start times to solve directly for an equilibrium state of flow for a single origin-destination pair with a single bottleneck and one route. Hendrickson et al. (1981) extended the problem to incorporate stochastic travel times uniformly distributed around the mean. Ben-Akiva et al. (1984) used the deterministic queuing model in conjunction with a stochastic model of departure time selection. Ben-Akiva et al. formulated continuous and discrete forms of the logit model to model departure time selection, and using this iteratively with the queuing model, acheived a steady state. Alfa and Minh (1979) used a stochastic queuing model developed by Minh (1977) to solve for travel time with a stochastic departure time selection model.

Henderson (1974) and Mahmassani and Herman (1984) used speed-density-flow relationships to solve for the travel time along links with time varying demand of vehicles for travel in the network. Like Fargier and Hendrickson, they solved directly for an equilibrium distribution. Hendersons' model also allowed for flexibility in the total demand dependent on the level of tolls whereas all previous models discussed, including Mahmassani and Herman, were short term models with known and fixed total demand.

Much of the above research has concentrated on single origin destination pairs with one route. Some researchers have extended the models to include route selection for a single origin destination pair connected by more than one route. Hurdle (1974) used a deterministic queuing model for one origin destination pair connected by two routes. However, this model did not directly incorporate costs of late or early arrival, only travel time, and therefore it did not consider the trade offs consumers may make between these cost components. Ben-Akiva et al. (1986) extended their logit model approach to include simultaneous selection of route and departure time for a single origin destination pair with two routes. Alfa (1981) extended the stochastic departure time selection model of Alfa and Minh (1979) to include a deterministic route selection model in which route and departure time are selected simultaneously. In the same work, Alfa simplified the model for application to the two route single origin destination problem, with deterministic route selection and stochastic temporal decisions.

Attempts at modelling more realistic networks, with multiple origin destination pairs and multiple routes, has been limited. Alfa (1989) has formulated and applied a heuristic approach, based on incremental loading of vehicle packets with simultaneous route selection and departure time selection. Another alternative is to consider the adaption of an existing route selection model to include departure time selection. This may be an attractive solution to modelling route selection and departure time selection simultaneously.

3.0 - THE CONTRAM MODEL

3.1 Description of the Model

CONTRAM is a route-assignment model which is able to deal with time-varying demand. It was developed at the Transport Road and Research Laboratory (Leonard et al. - 1978). Version 4, which is used in this research (Leonard and Gower - 1982), models traffic flow in an urban network in time intervals, with unsignalized and signalized links. Departures for each origin destination pair for each time interval are input to the model and assumed uniform over the length of the time interval as shown in Figure 2. Output of traffic performance, such as queue times, delay and degrees of saturation, are provided for each time interval. This output can be for network wide totals, or on a link by link basis. Some parameters, such as average speeds, are estimated for vehicles departing in each time interval for each origin-destination pair.

CONTRAM models traffic flow and determines route selection by grouping vehicles into packets of a size determined by the user. These packets are modelled as a unit. Using incremental loading, the route assignment technique is iterative and based on selection of shortest time paths through the network. Travel times for each link

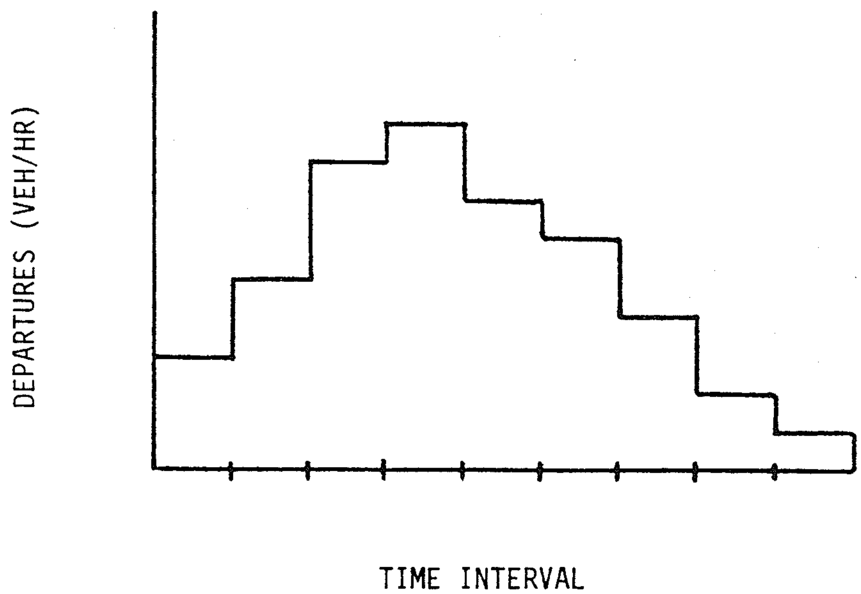


FIGURE 2 - Discrete Time approximation of demand

in each time interval are calculated based on the summation of the link's free flow travel time and the delay experienced by the vehicles. Queuing delay is based upon the approximation of vertical queuing at the downstream end of a link. CONTRAM does not take into account the effects of platoons of vehicles spreading out as they travel down a link. For signalized links, extra delay is incurred due to red phases and random delay, and give way links experience random delay. Delay due to the red phase of a signalized link is calculated as in the Webster-Cobbe formula, but the random delay uses a modified formula which provides for more realistic estimations in high degrees of saturation.

Because CONTRAM can model traffic flow in an urban network, and estimate travel times under time varying demand, adaption of it to aid in the problem of determining the temporal distribution of demand is attractive. However, it assumes that the input departure rates versus time interval demand function is constant and independent of the resulting traffic conditions. That is, there is no flexibility in departure time selection for the commuters modelled. Therefore, if CONTRAM is to be adapted to the problem of determining departure time selection, it must be used in conjunction with another model.

3.1 - Exceeding Storage Capacity in CONTRAM Version 4F

A number of sample networks have been coded, in preliminary runs of CONTRAM, in order to get a feel and understanding for use of the model and to clarify any difficulties that might arise. One problem did arise that required a significant amount of work to understand. Although initially it was not the purpose of this preliminary investigation to report difficulties in the final thesis, this particular problem did effect the rest of the research. It will therefore be discussed here.

On one of the preliminary hypothetical networks that was being tried an incongruity was found when the degree of saturation of a link was high enough to result in the formation of a queue that exceeded the storage capacity of a link. The saturation flow rate is defined as the maximum rate at which vehicles can depart from the end of a link, and is interpreted as capacity in vehicles per hour. The degree of saturation is the ratio of actual flow to the saturation flow rate. For unsignalized links the departures from the link in the time interval reported by CONTRAM exceeded the maximum possible departures consistent with service system theory. The number of vehicles discharged from a link should not exceed the saturation flow rate for that link multiplied by the length of the time interval. An example of this problem is considered next.

In the CONTRAM user's manual (Leonard et al. - 1982) a sample network is provided, as illustrated in Figure 3, with the associated network coding shown in Figure 4. Volumes traveling to destination 9003 were increased above those used in the manual with the result that link 524 of this network became full. This link has an input saturation flow of 1500 vehicles per hour. Time interval six is 15 minutes long, so the maximum possible departures is 375 passenger car units. However, CONTRAM's output (Table 1) indicates that 400 vehicles, or 25 more than possible, depart from link 524 in this time interval. This anomaly is also echoed by the output of spare thruput capacity of -25 listed in Table 1.

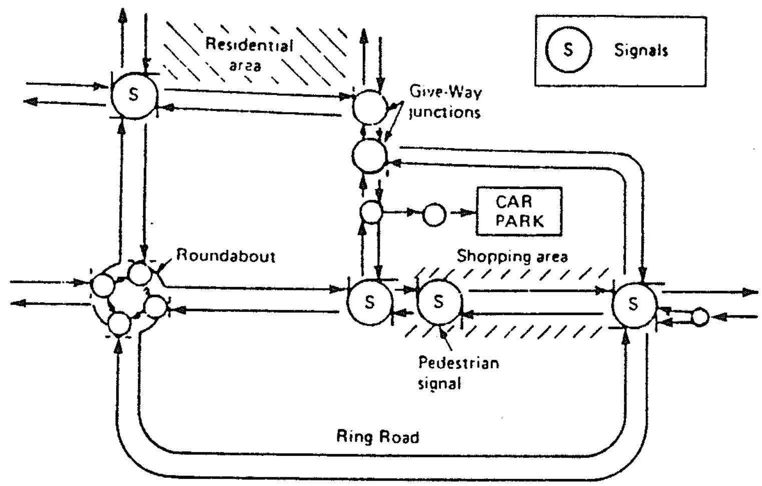


FIGURE 3 - TEST NETWORK (LEONARD AND GOWER - 1982)

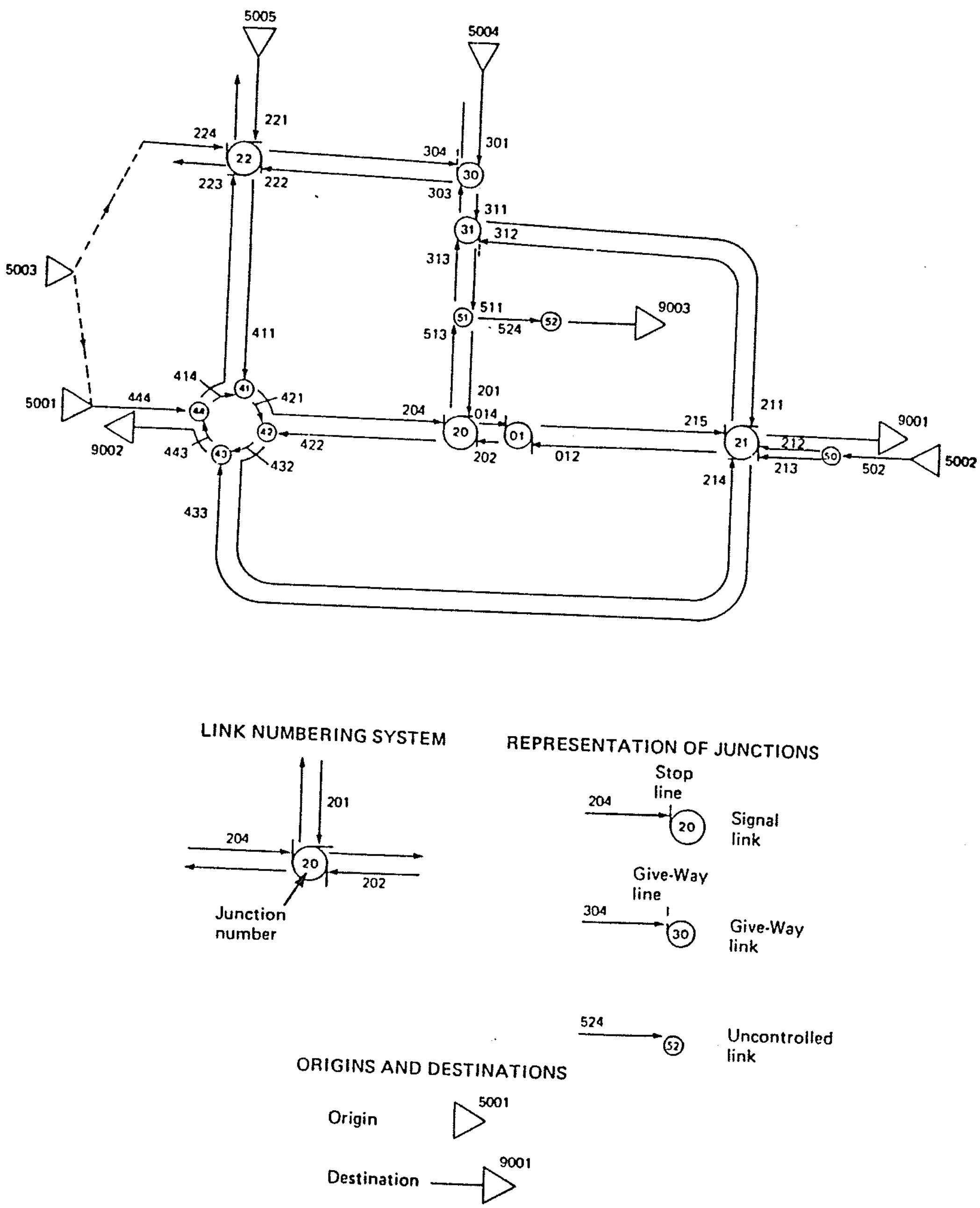


FIGURE 4 CODING OF THE TEST NETWORK (LEONARD AND GOWER-1982)

TABLE 1 - TRAFFIC DATA OUTPUT BY CONTRAM FOR LINK 524

TIME INTERVAL	INIT. QUEUE (PCU)	VEHICLE ARRIVALS (VEH)	DEPART. FROM QUEUE (PCU)	FINAL QUEUE (PCU)	SPARE THRUPUT CAPACITY (PCU)	LINK STORAGE LEFT	AVERAGE QUEUE TIME (SEC)
6	0	440	400	40	-25	0	80
7	65	780	805	40	-55	0	98

INIT. QUEUE - INITIAL QUEUE LENGTH
DEPART. - DEPARTURES

Average queue times for links which were full at the beginning of a time interval and the end of a time interval correspond to average queue times associated with queues of length equal to the storage capacity rather than the actual queue lengths. It was not clear as to what happened to vehicles queued in excess of the storage capacity. Were they removed from the system and not modelled or was the output indicating 400 departures in time interval six incorrect?

When examining the next time interval, that is time interval seven, the initial queue length is listed as 65, 25 more than the final queue length of the previous time interval (see Table 1). The initial queue length of a time interval should be equal to the final queue length of the previous time interval. The 65 vehicle queue length implies that no vehicles were unaccounted for and that only 375 vehicles departed in the previous time interval. The average queue time of 98 seconds corresponds more closely with an average queue length of 40 rather than 52.5 passenger car units. The CONTRAM user's manual defines average queue length as 1/2(initial queue + final queue).

These observations seem to answer the question posed earlier. What is believed to have happened is that when storage capacity was exceeded, calculations of average queue times were based upon queue lengths equal to the storage capacity instead of the actual queue length. Vehicles in excess of maximum queue remained in the system but their queue times were based only on the time spent in the portion of the queue within the storage capacity limit. Time spent further back in the queue was not included in the delay estimated. This would result in underestimated queue times and delay, and therefore underestimated travel times. Similar problems occurred for signalized links, but the problem was more difficult to assess because of the interrupted flow.

To investigate this hypothesis further, two runs of CONTRAM were made with the simple sample network shown in Figure 5. In the first run all links were given CONTRAM's estimated storage capacity based on their length and saturation flow. Traffic volumes were such that for certain consecutive time intervals the storage capacities of certain links were exceeded. In the second run, link 203 was given a very large storage capacity so that it would not overfill, as opposed to the 166 vehicle capacity estimated in the first run. Everything else about the link, and the rest of the network remained the same.

The results were that for time intervals before and after the time intervals in which link 203 was full for the first run, queue times, queue lengths, travel speeds, and other traffic data were exactly the same for both runs. However, during the time intervals in which this link was

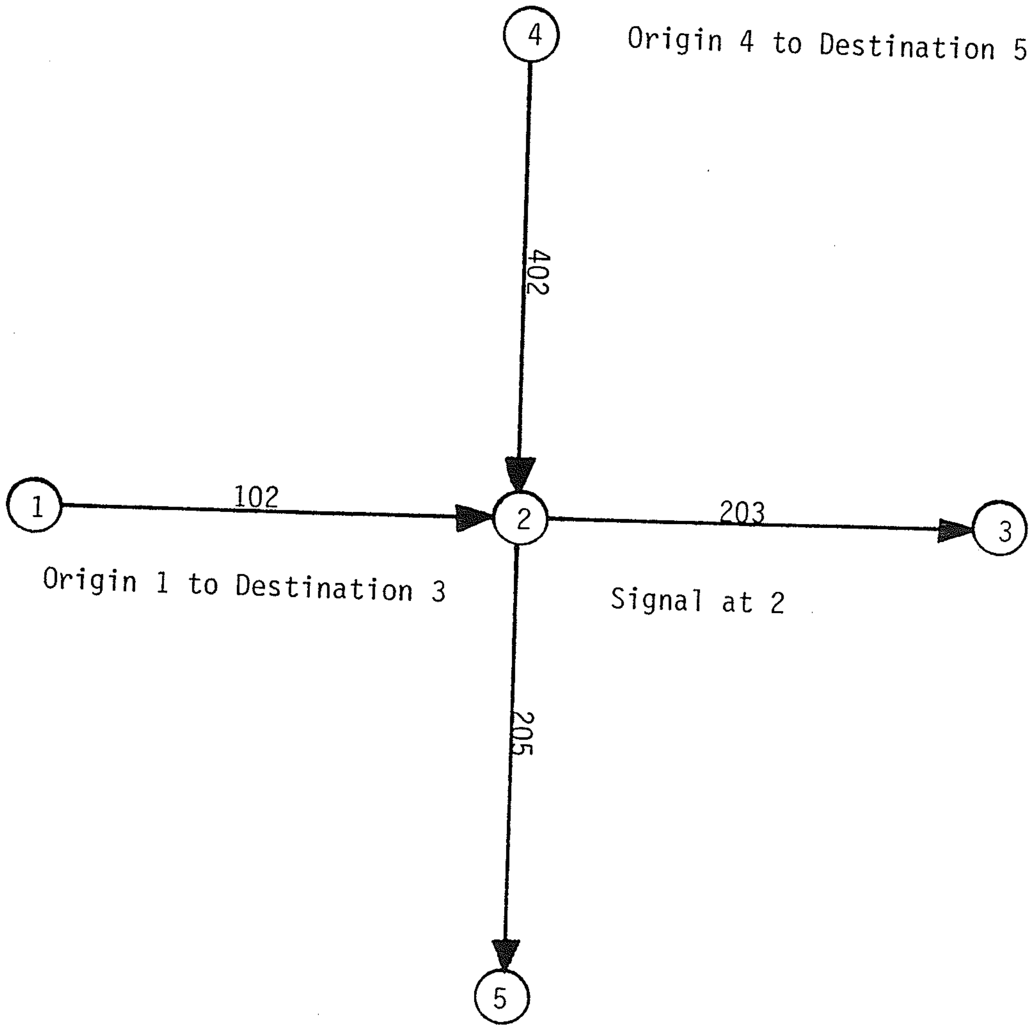


FIGURE 5 - TEST NETWORK 2

full in the first run, average queue times were lower and average speeds were greater than results of the second simulation when the link had very large storage. In the second run, final queues on the link in a time interval were consistent with the initial queues of the next time interval and the average queue times were consistent with the queue lengths experienced. The average queue times for link 203 in the first run, however, were consistent with the truncated queue lengths as was described earlier.

It is important to note that CONTRAM provides a warning when a link overflows such that it would interfere with the operation of an upstream link. When output of the two runs were compared, the links upstream of the over spilling link of the first run had identical traffic characteristics in each run. The only difference in the output for this link was the printing of the warning. Thus CONTRAM does not appear to actually model blocking back effects on traffic performance, it just provides a warning when this occurs.

Communication with the developers of the model revealed that this was an error in the program but had been corrected since, in a newer version of the model. With the version that is used in this research however it may be better to input very large storage capacities for links that are in danger of overflowing so that estimates of average speed and queue times are consistent with the queue lengths formed in the model. Because CONTRAM 4F does not model the effects of blocking back at the upstream links this would not affect the output traffic characteristics of the upstream links. However, it would then be up to the users to look more carefully for links that are in danger of, or are, overflowing. The warning provided by CONTRAM would no longer be printed due to the input large storage capacity. It must be emphasized that the observations discussed were consistent for a number of sample networks studied.

4.0 - DEPARTURE TIME SELECTION MODEL

As discussed earlier, there has been considerable work done with departure time selection modelling. The emphasis of this work is the adaption of CONTRAM to the problem by using it as a travel time estimator for a departure time selection model. Thus any model that has been already developed, or may be developed in the future, that bases departure time on costs that are a function of travel time can be used within this framework. Because CONTRAM is a commercial package, it cannot be modified to the problem of departure time selection within itself. The second model considering departure time selection therefore is quite distinct from CONTRAM. Departure time selection and route selection will be modelled sequentially rather than simultaneously. There are generally two components to departure time selection models, cost evaluation, and determination of the temporal distribution of traffic demand.

4.1 - The Cost Function

There have been a variety of approaches taken to estimate the cost to users who desire to arrive at their destination by a certain time. The previously cited models all considered cost functions from which commuter departure time decisions were derived. As noted in the discussion of these models, most approaches used for this problem have considered two components of cost to such travelers:

1) Cost associated with the time of arrival, either time spent at work before the work start time or the cost of time missed due to late arrival at work.

2) Cost of travel time from origin to destination.

The forms of these cost functions can vary. Hurdle (1974) only considered the second component of the cost function. Implicit in Hurdle's discussion, however, is an infinite cost of lateness. Many of the researchers have considered a linear sum of the two components. Henderson (1974) considered cost of earliness and travel time with late arrivals not permitted and extended the model to include tolls. Hendrickson and Kocur (1981) also included the cost of tolls. Models by Alfa and Minh (1979), Hendrickson et al. (1981) and Ben-Akiva et al. (1984) included cost for late or early arrival. Alfa et al. (1985) considered the effects of quadratic combinations of the two components of cost. Examples of forms of the cost model for component 1, cost associated with time of arrival, are shown in Figure 6. The total cost incurred to travelers would be estimated by adding the cost from models like those depicted in Figure 6 to the cost of travel time.

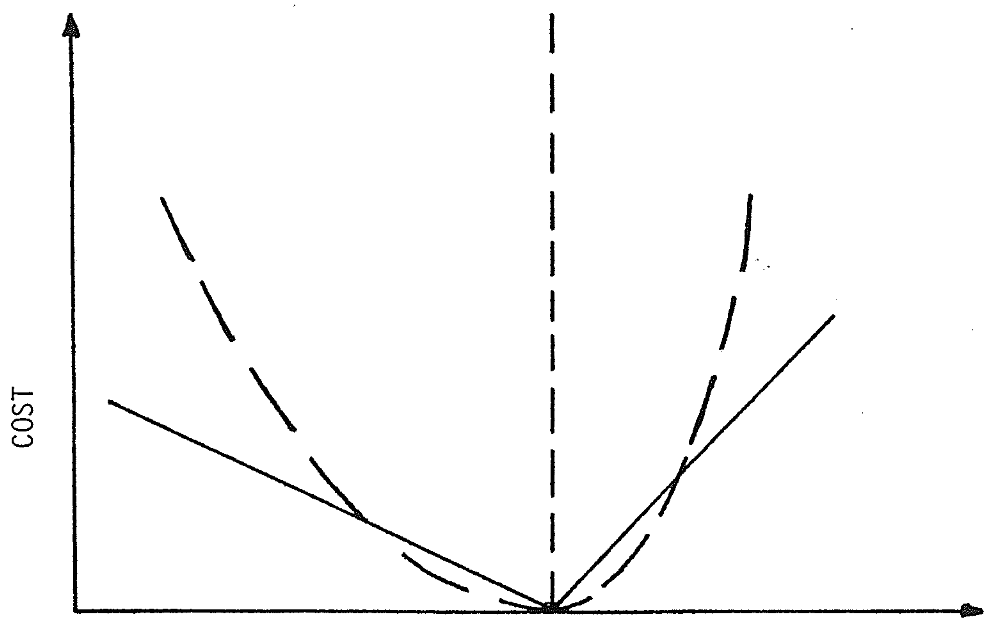


FIGURE 6- COST ASSOCIATED WITH THE TIME OF ARRIVAL

The following linear cost function was assumed for this research:

$$[1] \quad C_i = A(TT_i) + Bl(DT_i + TT_i - W_e)^+ + B_e(W_b - DT_i - TT_i)^+$$

where:

C_i = The cost to vehicles leaving for work in time interval i.

TT_i = Travel time for vehicles leaving in time interval i.

DT_i = Assumed departure time for vehicles leaving in time interval i.

W_b = Earliest desired arrival time.
W_e = Latest desired arrival time.

A, B_e, B_l are coefficients expressing the relative weights of cost of travel, cost of early time at work, and cost of lost time due to lateness respectively. The "+" superscript in the equation implies that only positive values of the bracket are considered, otherwise the value is interpreted as zero.

CONTRAM outputs one average speed from origin to destination for all vehicles of a given origin destination pair leaving in each time interval. The distribution of the speed around this average is unknown. Therefore, a deterministic cost function was assumed. The centroid of each time interval was used as the average departure time (DT_i in Equation 1) for all vehicles leaving in that time interval. The cost model reads the output of average speeds from CONTRAM and converts them to average travel times, TT_i, for use in Equation 1.

4.2 - The Temporal Distribution of Demand

Given the temporal distribution of costs, the determination of the distribution of traffic demand could be considered in many ways. It was decided to use a modified, deterministic, form of the stochastic model developed by Alfa and Minh (1979). This decision was made in the expectation that using a deterministic model would make it easier, and therefore quicker, to get the link between CONTRAM and the demand model into a usable form. The model could later be extended to the stochastic form if further research desired. Only the modified deterministic form of the model will be described here.

In essence, the problem is to determine the temporal distribution of the demand given the cost to vehicles departing in each time interval. To estimate the costs CONTRAM is used to model the traffic for a known distribution of demand. This model therefore considers the costs for a known distribution of demand and then reassigns the vehicles to a new distribution for subsequent remodelling by CONTRAM. The process continues iteratively until a steady state is reached if such a state exists. If a steady state does not exist, a range of output over many iterations must be analyzed.

Before describing the technique of reassignment, the following terms will be defined.

V_i - The volume of vehicles departing in time interval i in the previous run of CONTRAM.

C_i - The cost to vehicles departing in time interval i corresponding to the volume V_i.

V_i'- The new volume to be used in the subsequent run of CONTRAM

The problem at each iteration is to determine V_i' for all time intervals.

Given the distribution of costs as a function of time the expected reduction of cost of shifting departures from one time interval to another can be calculated by:

[2] $ER_{ij} = (C_i - C_j)^+$

ER_{ij} = the expected reduction in cost of changing departure times from time interval i to time interval j.

If the expected reduction in costs of shifting from time interval i to each of the other time intervals is totalled, the relative expected reduction in cost of shifting from time interval i to time interval j is obtained:

$$[3] \quad RRij = \frac{ERij}{\sum_{n}^{T} ER_{in}}$$

where:

RRij = The relative reduction in cost of shifting departure times from time interval i, to time interval j

T = The total number of departure time intervals.

Similar to Alfa and Minh (1979), it is assumed here that the volume of vehicles that change from time interval i to time interval j is proportional to RRij. However, in the deterministic form this would result in the most expensive time interval falling immediately to zero volume, even if its price was very close to other time intervals. To avoid this difficulty it is assumed that a certain portion of the vehicles do not shift their departure time intervals. This model assumes that the amount of vehicles that do not alter their departure time is a function of the difference in cost between their cost and the minimum cost. Thus for every time interval we define:

[4] $\beta_i = f[(C_i - C_{min})/C_i]$

β_i = The percentage of the total volume of vehicles, V_i, of a time interval that get reassigned to other time intervals.

This factor, helps to control the magnitude of changes from iteration to iteration. Its form could be determined through calibration with real data to help match model results with actual results.

Now consider the new volume of vehicles, V_i', of time interval i. β_i is the ratio of the vehicles that get reassigned to all less costly time intervals and $(1-\beta_i)$ is the proportion of the vehicles remaining, or more specifically $V_i(1-\beta_i)$ vehicles remain. From each more costly time interval, time interval i receives a volume of vehicles which gets added to the volume remaining. Thus by repetitive application of equations 2, 3, and 4:

[5] $$V_i' = V_i(1-\beta_i) + \sum_{n}^{T} RR_{ji}V_i\beta_j$$

Because of the nature of the CONTRAM model, a precaution had to be taken. From preliminary runs of CONTRAM, it appears that CONTRAM has difficulty modelling vehicles if the volume of a time interval falls near or below packet size. It seems that the model sometimes interprets volumes near or below packet size as zero volume. When this happens, no average speed is output by CONTRAM. It is possible that a time interval may fall out of the solution early with no demand, but later its cost may again become attractive. To allow for the possibility of a time interval re-entering the solution it was decided to model always at least one packet in each time interval. If V_i' given by Equation 5 should fall below packet size, it would be increased to the packet size by subtracting the required volumes from the other time intervals in proportion to the volumes in the other time intervals.

4.3 - The Computer Program and Processes

All of the above mentioned processes and calculations were put in the form of batch files and a computer program. Batch files were written to automate the link between the departure time selection model and CONTRAM. Many iterations between the two could then be run without interruption, and output from CONTRAM after each iteration was saved to separate files so that it was not overwritten. As well as reading the output from CONTRAM, calculating costs, and redistributing demand, the program edited the next input files to CONTRAM, and edited the batch files mentioned above so as to distinguish iteration numbers. The outline of the general procedure taken in the modelling process using the various programs and files is as follows.

Step 1: Given a network to be modelled, code the network for use by the CONTRAM model. This coding process includes deciding on the time frame of study, choosing the length of time intervals, coding the links in the network, and determining the origin-destination pairs.

Step 2: Input a starting solution of the distribution of departure rates with time for each origin-destination pair.

Step 3: Run CONTRAM with the various distributions of departure with time, until it has reached an an equilibrium solution.

Step 4: From the output of CONTRAM obtain the average straight line speeds for vehicles departing in each time interval for each origin-destination pair. Straight line speed is calculated by CONTRAM based on the travel time from the origin to the destination, and the straight line distance between the two.

Step 5: Use the average straight line speed and the distances to calculate average travel times (CONTRAM does not provide this in the output).

Step 6: Use the travel times to determine the costs by applying Equation 1. Use these costs to obtain the relative expected reduction in cost by applying

Step 7: Apply Equation 4 to determine a new temporal distribution of departures for each origin destination pair.

Step 8: Go back to Step 3. Repeat steps 3 to 7 until an equilibrium solution is reached or, because an equilibrium solution may not exist, until a set number of iterations are completed .

A more detailed outline of the process, explaining how the various programs and files are used in the above steps is given in Appendix A. A description of the program used for departure time selection is also provided along with its listing.

5.0 - THE SINGLE ORIGIN DESTINATION PROBLEM

Before testing of the joint model using realistic networks with multiple origin destination pairs could begin, it was decided to investigate the performance of the model on a single origin-destination pair with one bottleneck and one route. The first tests concentrated on analyzing convergence of the model. After confidence in these results were achieved, further test runs analyzed the effects of increased capacity, and/or incorporation of a flexible work start time plan by comparing various runs to a base case.

5.1 - Analysis of Convergence

The total number of commuters in the sample network is 3600 with 9 ten minute departure time intervals. The first departure time interval was 7:00 pm - 7:10 pm and the last is 8:20 pm - 8:30 pm. One additional time interval had to be modelled at the end of the time period to allow vehicles in the last departure time interval to clear the network. This time interval was 8:30 pm - 9:30 pm. A short flexible desired arrival time period from 7:55 pm to 8:55 pm was established for all vehicles, which may represent a degree of tolerance for an arrival period at the destination. All vehicles were assumed to have the same cost function, A=6,

$B_i=3$ and $B_e=1$ in Equation 1, assuming they belong to a similar group of travelers.

These coefficients are based roughly on work calibrating a cost model by Alfa et al. (1985). The term $ß_i$ was set, given by Equation 4, as follows:

$$[6] \quad ß_i = (C_i - C_{min})/C_i$$

Keeping all of the above conditions constant, iterations proceeded for two different starting solutions. In the first case, a uniform starting solution was used assigning equal numbers of vehicles to each departure time interval. In the second case, a spiked starting solution was used assigning almost all of the vehicles to the minimum free flow cost time interval, namely time interval 6, and only assigning one packet to each of the remaining time intervals as shown is Table 2. Results in each case could then be analyzed to determine if convergence occurs, and compared to determine if under very different starting solutions the results were still the same.

TABLE 2
STARTING SOLUTIONS

Departures (vehicles /hour) in Time Interval:	1	2	3	4	5	6	7	8	9
Unif. Start. Sol.	2400	2400	2400	2400	2400	2400	2400	2400	2400
Spiked Start. Sol.	60	60	60	60	21120	60	60	60	60

Unif. - uniform
Start.- starting
Sol. - solution

In the first case, with the uniform starting solution, after many iterations it was discovered that rather than converging to a state of equilibrium, a cyclic pattern developed with the peak time interval shifting sequentially between time interval 3, 4, 5, and 6, with peak demands of about 7500-8200 departures per hour in each of these. Observations of the demand distributions for each of these peaks showed that they were repetitive. For example Figure 7 shows that about every seven or eight iterations a distribution is approximately repeated. In Figure 7 the distributions for iterations 11, 18, and 28 are superimposed over each other. When looking at the volume in certain time intervals in successive iterations (ex. Figure 8) it is apparent that the cycle is quite pronounced and also that the cycle is well established within about five to ten

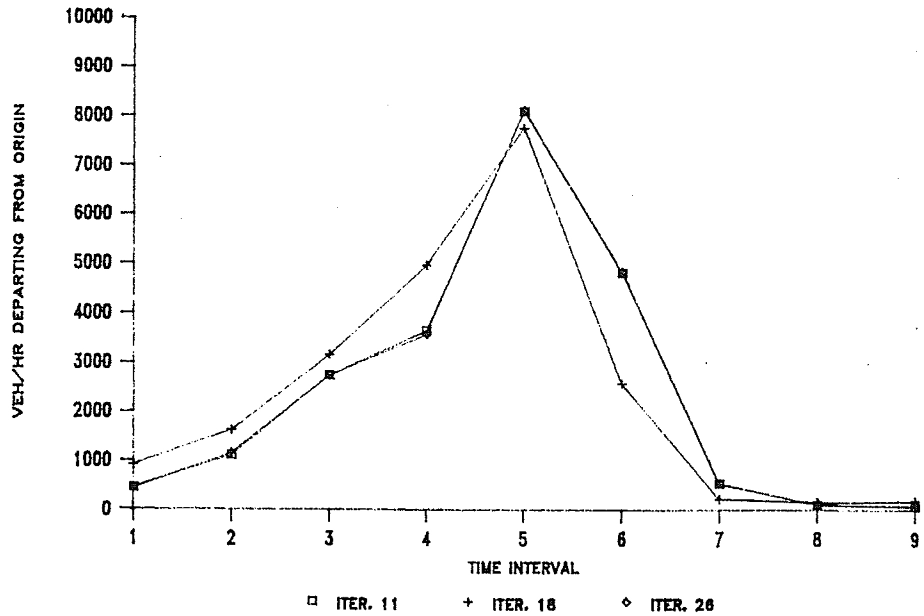


FIGURE 7 - DISTRIBUTION OF DEPARTURES WITH TIME
3 ITERATIONS FOR UNIFORM STARTING SOLUTION

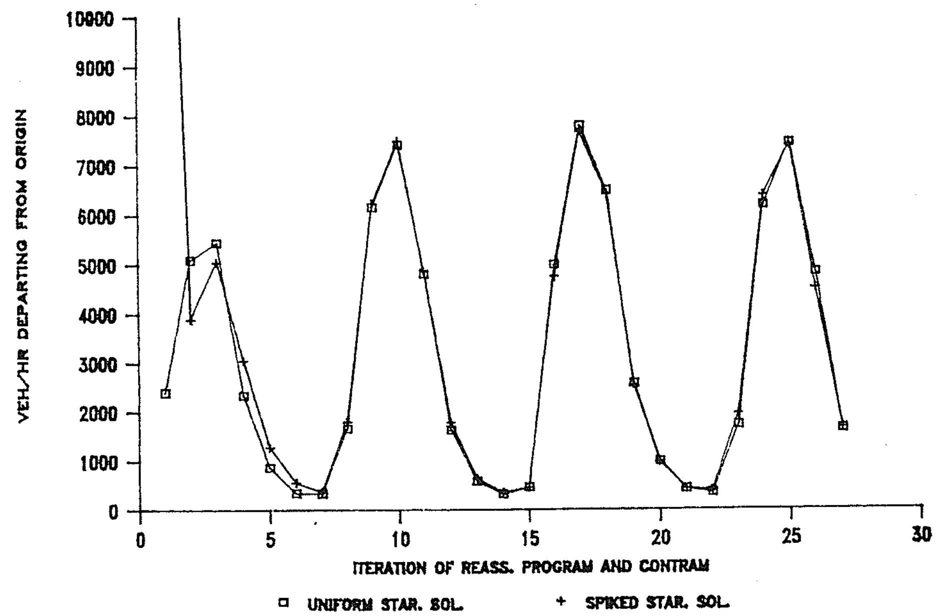


FIGURE 8 - DEPARTURES IN TIME INTERVAL 6 AS FUNCTION OF
ITERATION FOR UNIFORM AND SPIKED STARTING SOLUTION

iterations. In Figure 8 the pattern of the cycle for both starting solutions are superimposed on each other. Within very few iterations the cycles are almost indistinguishable.

Although an equilibrium state was not achieved, a strong cyclic pattern was apparent, and the nature of this cyclic pattern was independent of the starting solution. These observations justify proceeding with further investigation.

5.2 - Capacity Increases and Flexible Work Start Times

Since a level of confidence in the consistency of the solutions obtained from the problem has been obtained the effects of capacity increases and the adoption of flexible work start times can be investigated. If the results are realistic, then there is justification in pursuing the research to more complex networks. As this investigation continues, issues related to convergence will be addressed as they arise.

The base case for this investigation will use the same network as above with the same saturation flow rate. However, to ensure that volumes decay to the minimum on both sides of the peak time intervals, the total volume of the vehicles was reduced to 2100 vehicles. A rigid work start time of 8:00 am was assumed for all vehicles in the base network, thus We=Wb=8:00. The same cost coefficients of the previous section for travel time, lateness, and time spent at work early were used . Three subsequent conditions in the network were investigated using the CONTRAM and departure time model link. The four situations are summarized in Table 3. Alternatives 2 and 3 investigate the effects of a flexible work start time period incorporated at the destination.

TABLE 3 - FOUR NETWORK CONDITIONS CONSIDERED

Network	Total Vehicles	Saturation Flow(veh/hr)*	Work Start Time
Base Case	2100	3600	8:00am
Alt. 1*	2100	5400	8:00am
Alt. 2	2100	3600	7:40am-8:10am
Alt. 3	2100	5400	7:40am-8:10am

*Alt.-Alternative
veh/hr - vehicles per hour

The base case fell into a cyclic pattern quite quickly, consistent with previous results, with peaks shifting between time intervals 4, 5 and 6 as shown if Figure 9, and a maximum peak volume of about 8300 departures per hour in time interval 4. Only fifteen iterations were performed because of the confidence in the cyclic nature of the problem as identified earlier.

Alternative 2, that is the one with increased capacity, yielded interesting results. This time it was apparent that

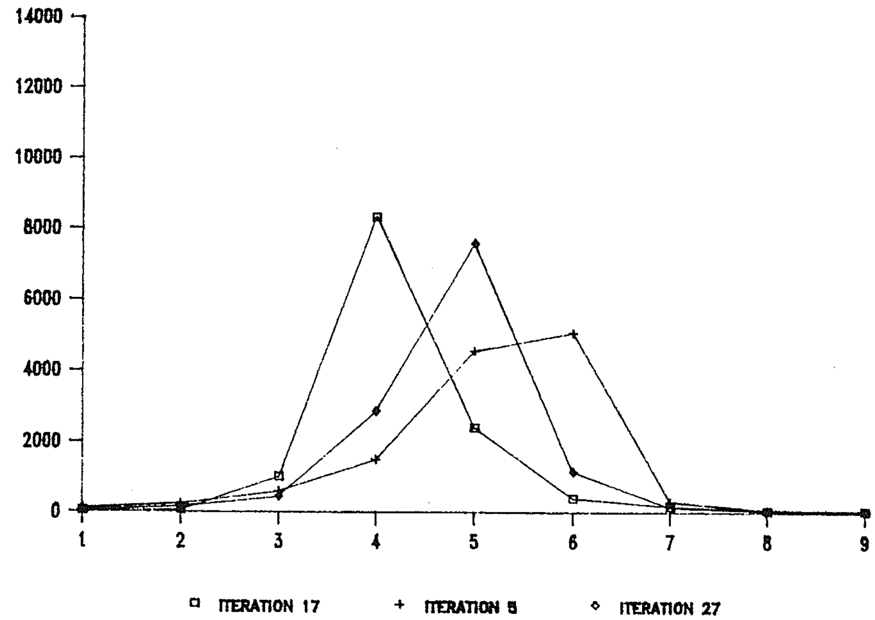


FIGURE 9 - SHIFTING DEMAND OF BASE SCENARIO
FOR UNIFORM STARTING SOLUTION

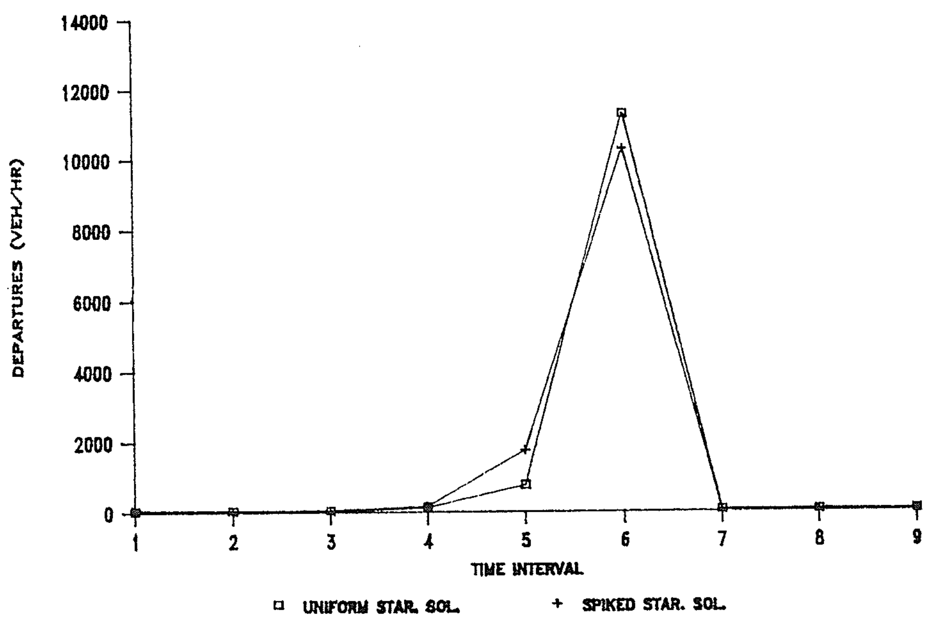


FIGURE 10 - EQUILIBRIUM DISTRIBUTION OF DEMAND
ALTERNATIVE 1, INCREASED CAPACITY

the system was converging, although very slowly. After 16 iterations the changes in cost were small enough that the subjective decision was made to stop the iterations. The same network was investigated using a spiked starting solution. After twelve iterations the iterations were stopped as the system was again converging to an equilibrium solution. The final distributions of volume as a function of time interval for both the spiked starting solution and the uniform starting solution are superimposed on each other in Figure 10. It is seen that the final distributions are very similar at the point in which the iterations were halted. Thus, although there seems to be some point at which the system changes from a cyclic pattern to an equilibrium state, the final state still appears to be independent of the starting solution. A sensitivity analysis of the single-origin destination problem, in which capacity was increased slowly showed that the system switched from cyclic behavior to an equilibrium solution at a capacity of 4500 vehicles per hour.

Because the system converges for the increased capacity case, comparison between this case and the base case is a little more difficult. However, the peak of the equilibrium distribution for Alternative 2 is to the right of the shifting peaks of the base case and experiences higher volumes. In short, more vehicles leave over a shorter time at later times when capacity is increased. This observation is consistent with research of Alfa and Minh (1979), Alfa et al. (1985), and Hendrickson and Kocur (1981). Ben-Akiva et al. (1986) did experience a shift of demand to a later time when capacity was increased, but their equilibrium distribution was more spread out, that is with lower peak volumes over a greater time.

The incorporation of flexible work hours (Alternative 3) also resulted in convergence to an equilibrium solution, but, as shown in Figure 11, the final distribution was bi-modal with a peak of approximately 8000 departures per hour during time interval 4 and a second lower peak of 3200 vehicles per hour at time interval 6. The first peak results in a rapid build up of vehicles at the bottleneck resulting in a state of high over saturation and very long queues. At this point vehicles stop arriving and do not begin departing again until the queue at the bottleneck dissipates. The flexible work start time gives commuters more flexibility in departure times which they can utilize to avoid congestion. Alfa et al. (1985) predicted a lower uni-modal peak with the volumes spread out over greater time when a flexible work start time plan was incorporated.

When the capacity was increased for the flexible work start time case, that is Alternative 3, the system converged to the plateau shaped distribution shown in Figure 12 with

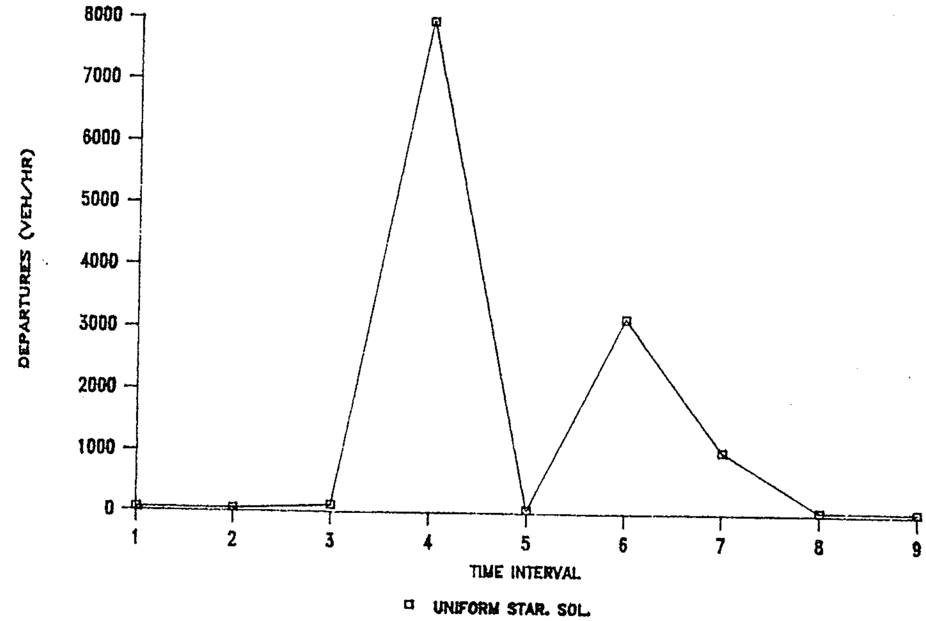


FIGURE 11 - EQUILIBRIUM DISTRIBUTION OF DEMAND ALTERNATIVE 2, FLEXIBLE WORK START TIME

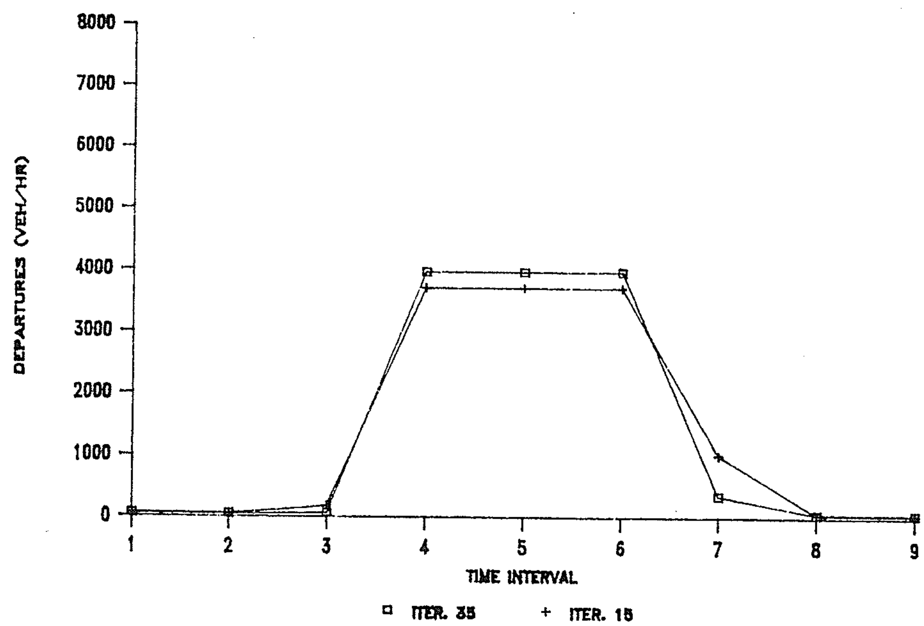


FIGURE 12 - EQUILIBRIUM DISTRIBUTION OF DEMAND ALTERNATIVE 3 INCREASED CAPACITY AND FLEXIBLE WORK START TIME

much lower peak volumes, about 4000 departures per hour in time interval 4, 5, and 6 at the same time. Examination of the network showed that the increased capacity resulted in negligible queueing. There is, therefore, no congestion for commuters to avoid and as a result the volume spreads out evenly over the three minimum cost time intervals. In Figure 12 the distribution after 15 iterations is compared to the distribution after 35. Alternative 3 therefore follows more closely to the behavior predicted by Alfa et al. (1985). For the method used here the existence of a bi-modal equilibrium state seems to be related to capacity in some way. A sensitivity analysis in which the capacity was slowly increased from that in Alternative 2, showed that the equilibrium solution shifted from a bi-modal solution to a plateau shaped distribution at a capacity of 4400 vehicles per hour. In either the bi-modal or uni-modal situation, there is still a greater spread in time of the demand when compared to the base case, which is what is expected.

5.3 - Conclusion

In general terms, adapting CONTRAM to the problem of determining the temporal distribution of peak traffic demand by incorporating it with the departure time model described produces general results for the single origin-destination problem that are consistent with what is expected. Increased capacity results in more cars departing later over a shorter period of time. Adopting flexible work hours results in vehicles moving through the system over a greater time. The existence of a bi-modal distribution which seems dependent on capacity is a situation that has not been noted in past research however. Whether this is realistic or not remains to be investigated. Given that the majority of the results are consistent with what is expected, further investigation using more realistic, multiple origin destination networks is warranted.

6.0 - MULTIPLE ORIGINS AND DESTINATIONS

Having established that the developed method provides reasonable answers for the single origin-destination problem, it was applied to a more complicated network, with multiple origin-destination pairs, and multiple routes. The goals of this approach were to determine if the results remained reasonable and to determine how adaptable CONTRAM was to this more realistic situation. Factors influencing the multiple origin-destination network that do not affect the single origin-destination problem are the availability of multiple routes on which to travel and interaction between vehicles of different origin destination pairs due to the sharing of common links. The selected network also included traffic signals and giveway links thereby introducing the additional effects of interrupted flow conditions.

6.1 The Base Networks

Two issues were to be addressed by the base networks used to study the multiple origin-destination study. It was desired both to increase the complexity of the network used for study and to get the CONTRAM/departure time selection model working properly for the multiple origin-destination problem and also to get fairly quick initial results. It was decided to use the sample hypothetical network provided in the CONTRAM users' manual (Leonard and Gower - 1982) (Figure 3 and 4 in Chapter 3) for the physical network. This network is relatively simple, but provides a good start on the multiple origin-destination pairs and multiple routes problem. The coding of this network is repeated in Figure 13. Truck and bus volumes and fixed route data, used by Leonard and Gower were removed from the network. Volumes between the origin-destination pairs (O-D pairs) were also changed. All traffic signals were put on a fixed time plan, while in the sample runs of the user's manual some operated on an optimized timing for some of the time intervals. Leonard and Gower used a time frame of three hours, with time intervals of inconsistent length, using more refined time intervals for peak periods. The time frame and length of time intervals was changed for the purposes of this research, to the same as used in the previous sections.

The modifications mentioned above reduced the number of origin-destination pairs to five in total. Table 4 shows each pair and the total volume of vehicle demand to be moved for each over the period of study.

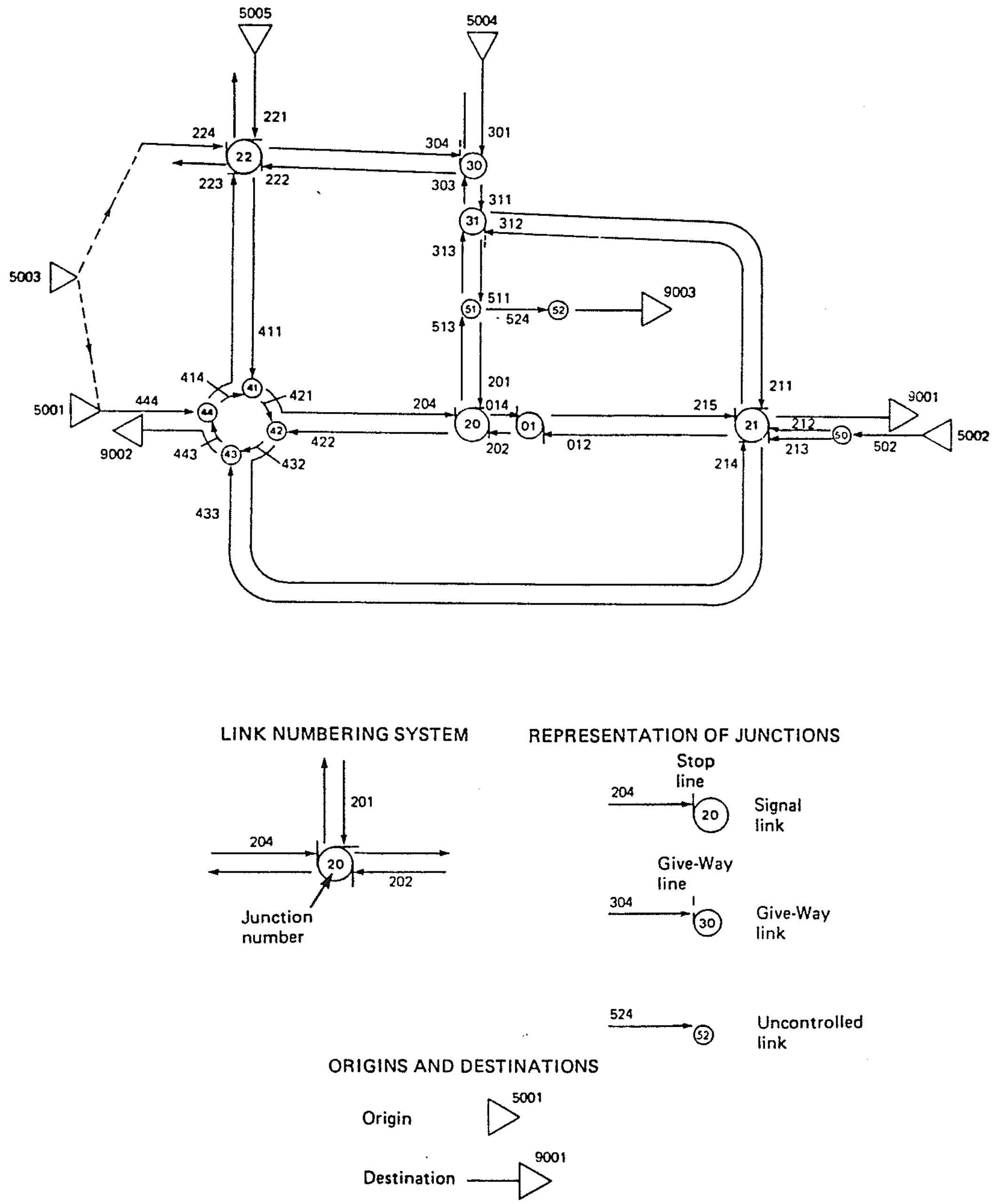


FIGURE 13 CODING OF THE TEST NETWORK (LEONARD AND GOWER-1982)

TABLE 4 - ORIGIN DESTINATION PAIRS USED
FOR THE MULTIPLE O-D NETWORK

No.	Orig.	Dest.	Total Demand
1	5001	9001	1350 (veh.
2	5001	9003	465
3	5005	9002	908
4	5003	9003	293
5	5002	9002	188

Orig. - origin
Dest. - destination
veh. - vehicles

For the initial investigation, the physical nature and saturation flows of the sample network remained the same as provided in the User's Manual. The description of the links for input into CONTRAM is given in Table 5. The departure time selection model was extended to incorporate multiple origin and destination problems. Links in danger of overflowing were given large storage capacities because of the problem outlined in Section 3.2.

Two base studies were considered. The first assumed a single desired arrival time of 8:00 am for all origin-destination pairs. The second network assumed that all origin-destination pairs had two desired arrival times, 7:30 am and 8:00 am. This second network used the same total demand as the first study, and assumed an equal split of demand between the two desired arrival times. For both base networks 9 time intervals each of ten minutes each were modelled between 7:00 am and 8:30 am plus the extra time interval provided for vehicle clearance.

TABLE 5 - LINK DESCRIPTION

UNSIGNALIZED LINKS

LINK No.	CRUISE TIME	LENGTH (METRES)	SAT'N FLOW *	STORE. CAP. **	JUNCT. No. ***
301	40	500	1500	9999	30
303	1	10	1600	999	30
311	1	10	1600	999	31
313	20	240	1600	9999	31
414	4	40	2500	999	41
421	4	40	2500	999	42
432	4	40	2500	999	43
443	4	40	2500	999	44
502	60	600	4200	999	50
511	20	240	1600	999	51
513	20	200	1600	999	51
524	4	30	1500	999	52

GIVEWAY LINKS

LINK No.	CRUISE TIME	LENGTH (METRES)	SAT'N FLOW	STORE. CAP.	JUNCT. No.	GIVESWAY TO LINK	
304	75	1000	600	180	30	303	301
312	100	1300	600	200	31	311	313
411	40	500	2000	999	41	414	
422	80	1000	1500	999	42	421	
433	300	5000	3000	999	43	432	
444	80	1000	3000	999	44	443	

SIGNALIZED LINKS

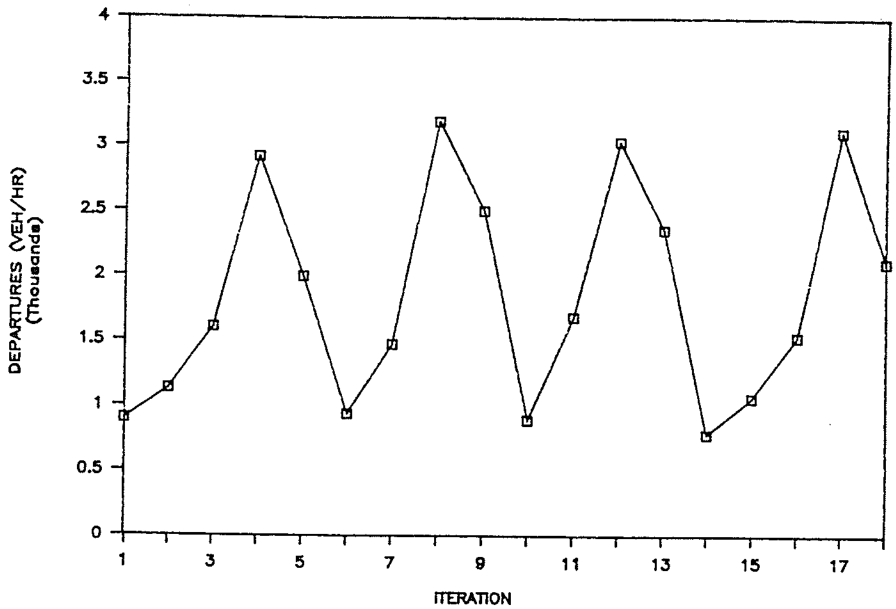
LINK No.	CRUISE TIME	LENGTH (METRES)	SAT'N FLOW	STORE. CAP.	JUNCT. No.
12	75	900	1500	999	1
14	4	50	1500	999	1
201	20	200	1600	999	20
202	4	50	1600	999	20
204	80	1000	1500	999	20
211	100	1300	1800	999	21
212	10	100	1500	999	21
213	10	100	3000	999	21
214	300	5000	3000	999	21
215	75	900	1600	999	21
221	40	500	1500	999	22
222	75	1000	1800	999	22
223	40	500	2000	999	22
224	90	1000	1500	999	22

* SATURATION FLOW RATE
** STORAGE CAPACITY
***JUNCTION NUMBER

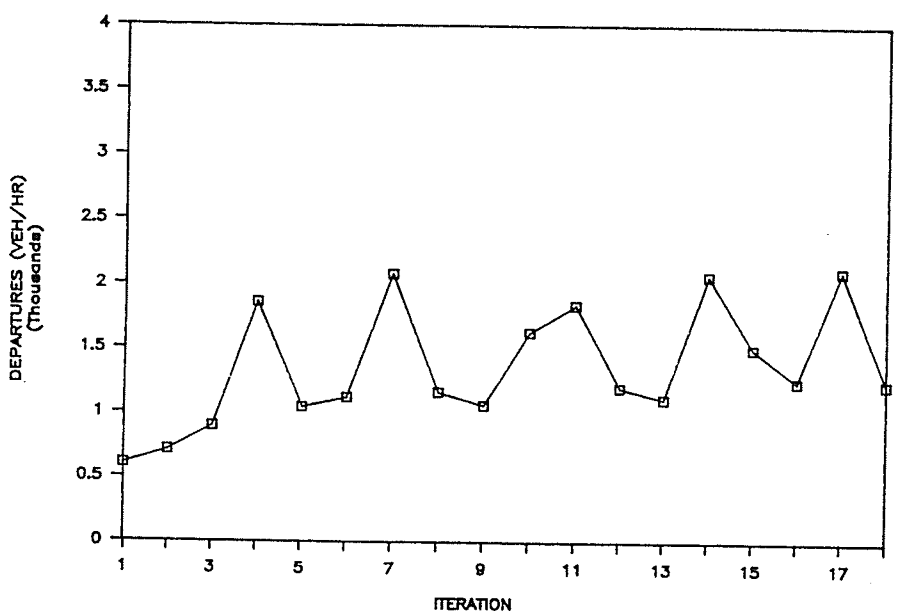
A number of iterations were performed and system behavior examined as a function of iteration, across the time intervals. The initial study at this point was somewhat macroscopic, examining the behavior of demand for each origin-destination pair over the iterations performed. Only a small sample of the corresponding graphs and plots can be presented as expanding the network to five O-D pairs greatly increases the amount of output and work involved when studying the behavior of the network over nine time intervals.

6.2 - Base network 1, the single desired arrival time.

Results for the single desired arrival time base study showed that for most O-D pairs, behavior was similar to that of the single origin-destination problem. Departure rates in the time intervals as a function of the iteration were fairly cyclic, although the cycles are not as well defined as in the single O-D study, and showed amplitudes that were more irregular as shown in Figure 14. The amplitudes of the cycle were quite large. The time interval of peak demand for each origin destination pair shifted in a fairly regular manner during the iterations. For most pairs, the peak shifted between time intervals 4, 5, and 6. Some time intervals showed more irregular amplitudes of variation but these were



(A)



(B)

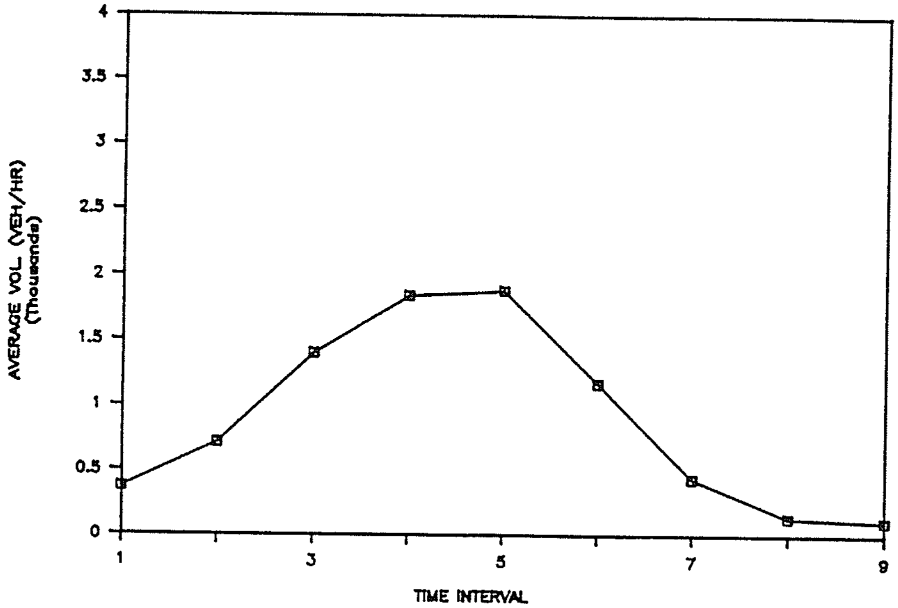
FIGURE 14 - DEMAND OF TIME INTERVALS AS FUNCTION OF ITERATION. (A) TIME INTERVAL 4, O-D PAIR 1. (B) TIME INTERVAL 4, O-D PAIR 3

time intervals of lower volumes such as off peak time intervals, or those O-D pairs with much lower total volumes. The absolute value of these variations were relatively small compared to the peak time intervals.

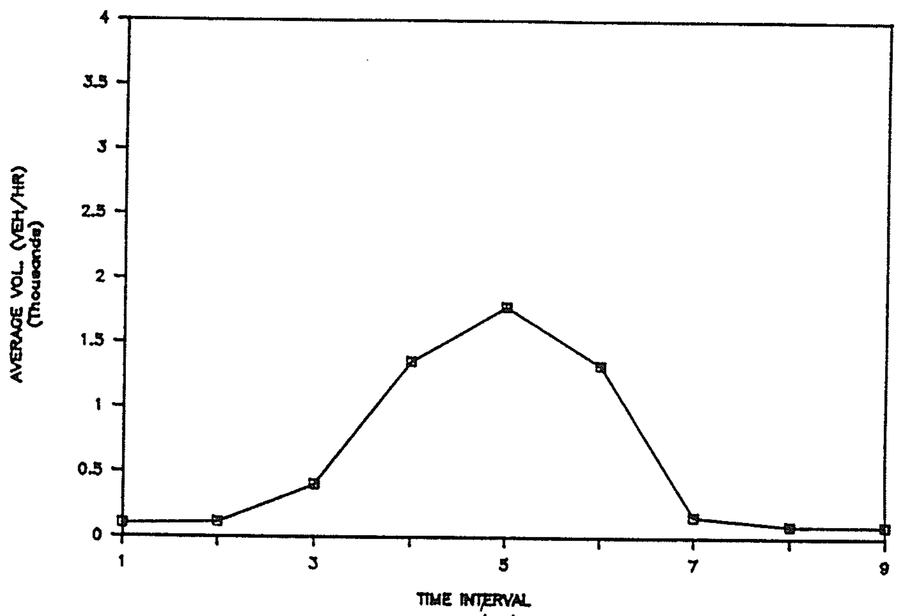
To present the results of a network in which cyclic behavior occurred Alfa (1989) considered the average distribution of departures over the time intervals for each O-D pair. The volumes of departures in each time interval were averaged over the total iterations. This approach will be adopted here to aid in the comparison between alternative networks. The average distributions for O-D pairs 1 and 3 are presented in Figure 15. The average distributions aid comparisons, but are not entirely representative of the behavior of the system. Because of the amplitude of changes from iteration to iteration, behavior of the system in an iteration can be very different from the last, and the nature of the distributions vary significantly from the average.

6.3 - Base network 2 - two desired arrival times.

It was felt that modelling multiple desired arrival times in the peak hours was a more realistic approach. Any central business district for example, is likely to have many businesses, and destinations with more than one work start time. The second base study, with two work start times at



(A)



(B)

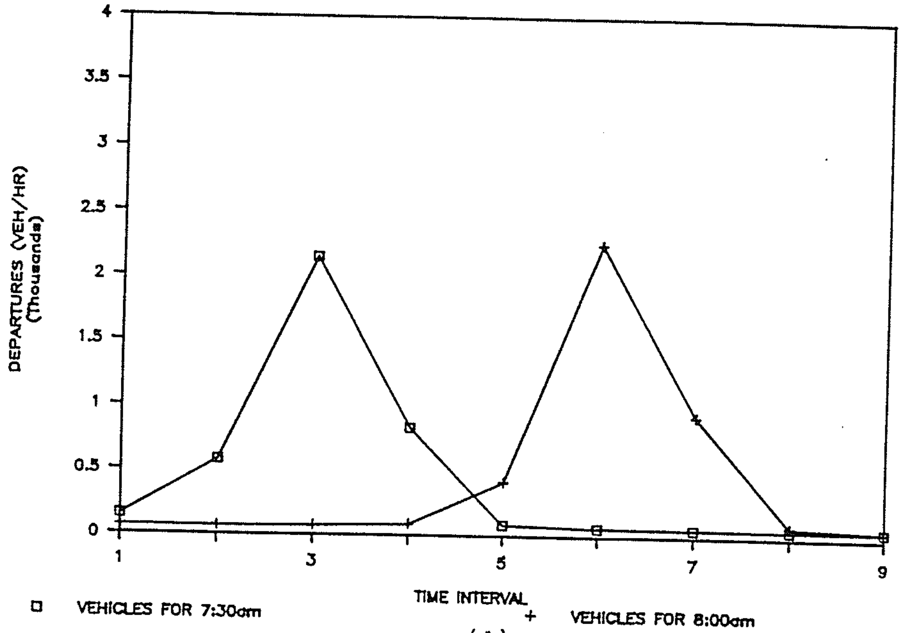
FIGURE 15 -AVERAGE DISTRIBUTION OF DEPARTURES
(A) O-D PAIR 1, (B) O-D PAIR 3

each destination similar to the research by Alfa (1989), was therefore investigated.

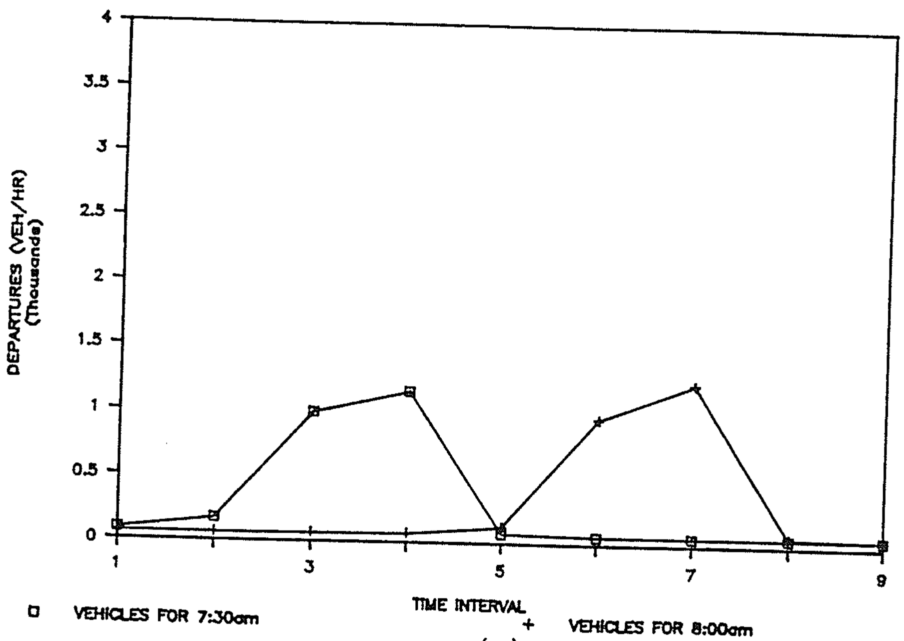
One important observation from the results was that for a given O-D pair the cycle of departures for vehicles in each desired arrival time group were very similar to each other, resulting in very similar average distributions with little overlap between the distributions. It is believed that this situation occurred because the separation in time between the two desired arrival times was high enough, and the volumes corresponding to each were low enough, so that those in the first were able to clear the network before any significant interaction between the two groups of vehicles occurred. The two groups therefore behaved independently. In Figure 16 the average departure rates of vehicles in each desired arrival time group are considered separately, to distinguish between the behavior of vehicles in each group. The total departure distribution would be obtained by adding the amount of departures for each group together.

Origin-destination pair 5 had volumes that were too low relative to the packet size so that it maintained a relatively uniform distribution of demand because the departure time selection model maintained a minimum departure volume in each time interval. Origin-destination pair 5 was therefore not considered in the rest of the analysis.

The results of this analysis were significantly



(A)



(B)

FIGURE 16 - AVERAGE DISTRIBUTION OF DEPARTURES BASE NETWORK 2. (A) O-D PAIR 1 (B) O-D PAIR 3

different than the single desired arrival time results. One primary difference was that the time intervals of peak departures for many of the O-D pairs, did not shift over as many time intervals during the iterations. After the first three iterations, vehicle departure distributions for vehicles in each desired arrival time group in O-D pair 1 maintained a single peak time interval, although the volume still varied. Origin-destination pairs 2 and 4 had one predominant peak time interval for vehicles in each desired arrival time group, with an occasional shift to a neighboring time interval, and the peaks for origin-destination pair 3 shifted equally between two time intervals.

The second major difference between base network 1 and base network 2 is that the variation of departure volumes in a given time interval for base network 2, as shown by Figure 17, had a significantly lower amplitude relative to the average volumes. This issue will be discussed in the rest of the paper in terms of a parameter called the percent difference, defined as the average value of all the iterations divided by the absolute value of the difference between the value in any one iteration and the average value. As shown in Figure 17 B, in some circumstances the variation of volumes seemed more random but still within a narrower band, relative to the average volume, than base network 1.

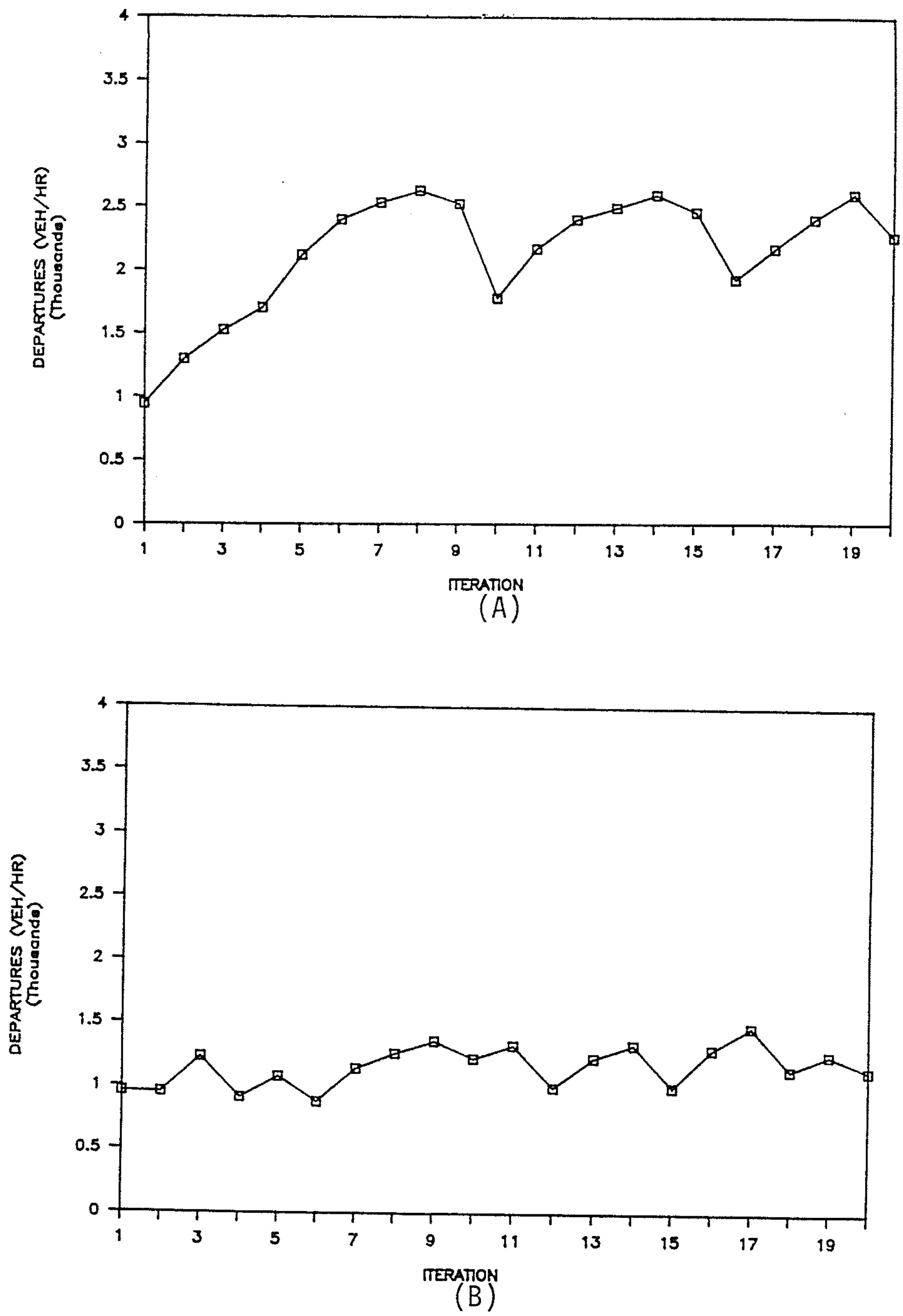


FIGURE 17 - DEMAND OF TIME INTERVAL AS A FUNCTION OF ITERATION. BASE NETWORK 2. (A) TIME INTERVAL 4, O-D PAIR 1. (B) TIME INTERVAL 4, O-D PAIR 3

6.4 - System Behavior

The above analysis considered the behavior of demand over time. It is also important to compare the traffic behavior in the system which, due to capacity restraints, interrupted flow, and the interaction of vehicles, may not reflect the behavior of the demand. To consider system behavior, first of all system wide delay over the iterations for each network was considered. This is the total time spent in queue, and any random components of delay that may occur, of all vehicles in the network. It is an important parameter for planning purposes and signal design. A more microscopic analysis was then carried out. The volume of arrivals in each time interval at the downstream end of a link over the period of study was considered. These types of measurements, as will be discussed further in a later section are also important in comparing various alternatives for network improvement.

As demonstrated in Figure 18, the behavior of the two systems is quite different. The system wide delay is much less, on average, for the network with two desired arrival times. This is somewhat expected, since earlier results suggested the two sets of vehicles in each work start time were far enough removed that they did not effect each other.

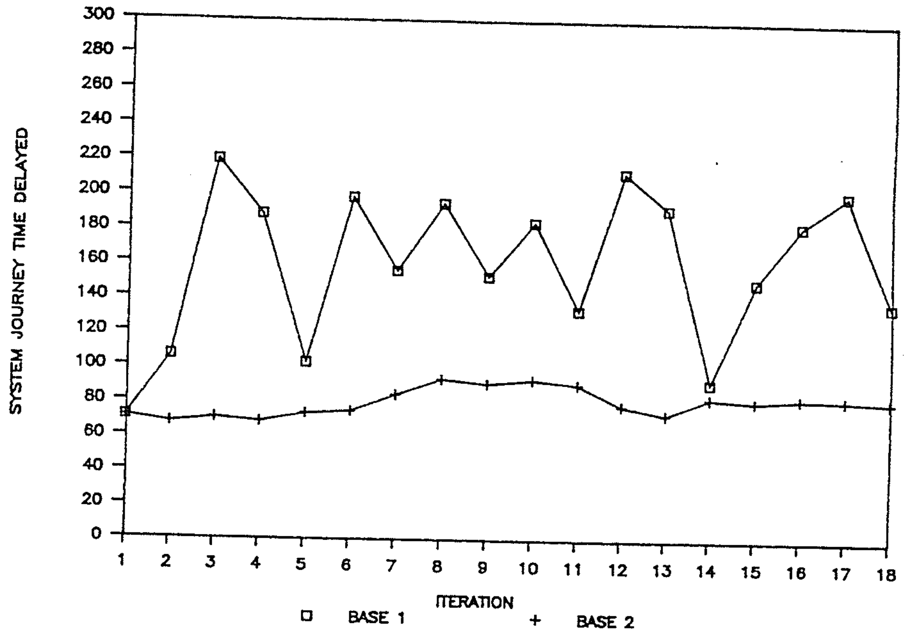


FIGURE 18 - TOTAL SYSTEM DELAY AS A FUNCTION OF ITERATION

The second important observation is that the variation from iteration to iteration is quite different. For base network 1 the variation of system delay did not show consistent amplitude in the cycle of variation, with large percent differences. The delay of base network 2 showed very small percent differences in each iteration, with values of delay never very far from the average.

Examination of base network 2 revealed that it was much less congested in each iteration than base network 1. Many links that were congested in base network 1 were never, or rarely congested in base network 2. This would allow volumes of vehicles in any time interval to increase without as much of an increase in delay as would be encountered for the same increase in volume in an oversaturated network.

Link 204 was picked for the observations for behavior in a field location in the network. This link would be used by vehicles of origin destination pairs 1, 2, and 3, and therefore there was a significant level of mixing of vehicles from different origin-destination pairs. The vehicle arrivals at this link in each time interval were determined from the CONTRAM output, and similar to the departures in each time interval, plotted against the iterations. Average distributions of arrivals with time were also considered.

Base network 1 displays an inconsistent amplitude of variation of total arrivals, although relative to base network 2 the variation was within a narrower band showing a smaller percent difference than the cycle of departures. A sample of the results is shown in Figure 19. Most of the time intervals behaved in a similar fashion to time interval three (Figure 19-A), although time interval 6 and time interval 7 showed larger variation. The variation for time interval 7 is shown in Figure 19-B. The distribution of arrivals across the time intervals was much more uniform than the distribution of the departures. These results are likely due the effects of capacity constraints. Links upstream of 204 operate above capacity and therefore discharge vehicles at a fairly uniform rate. Downstream behavior consequently reflects the rates of discharge of these rather than the actual demands.

For base network 2 the variation of arrivals at link 204 from iteration to iteration was even more regular than that of the single work start time. Examples of this are given in Figure 20. However, the distribution across the time intervals is less uniform showing definite bi-modal distributions in many of the iterations. Lower congestion, in this case, has allowed the distribution of demand to be reflected in the arrivals at link 204.

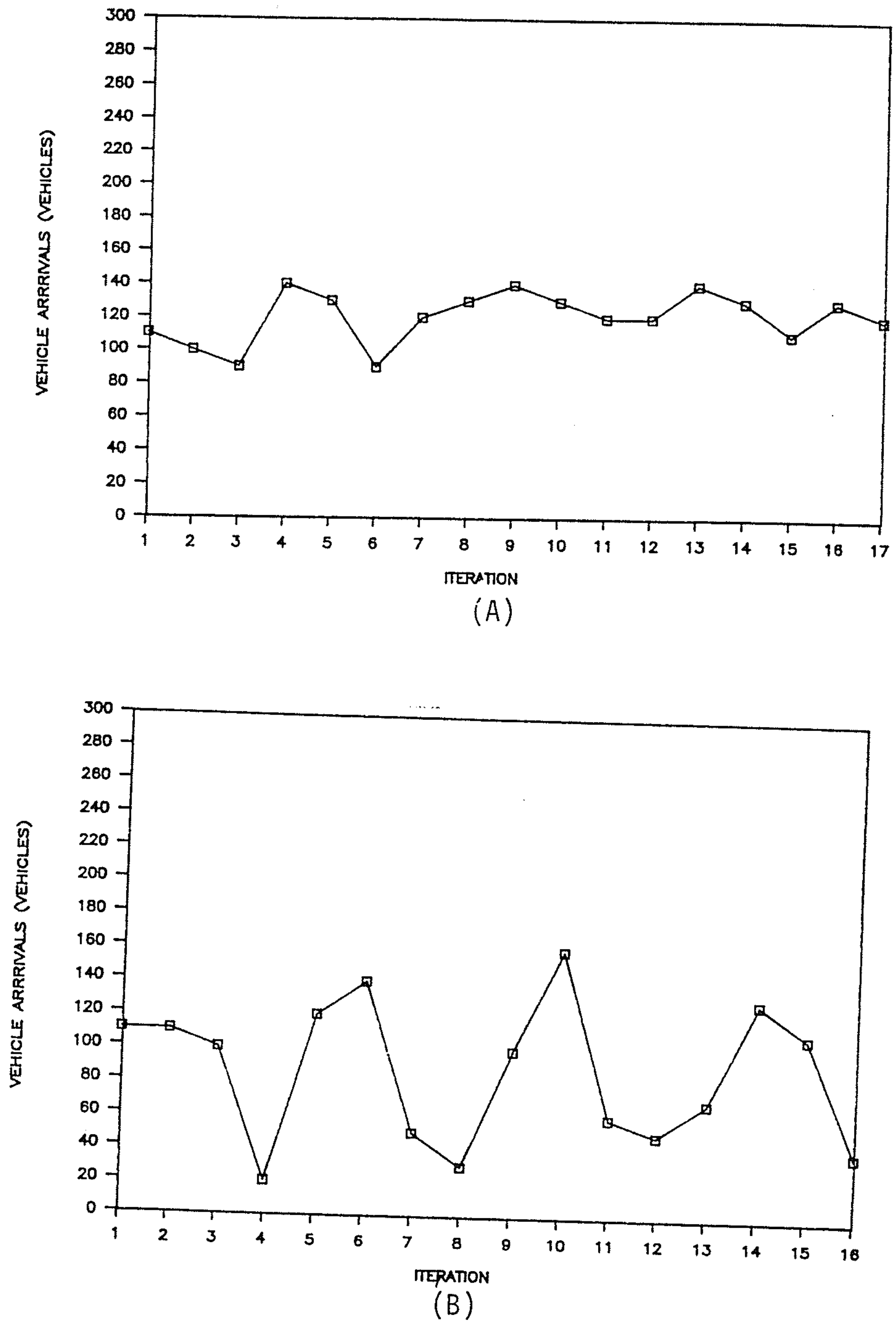
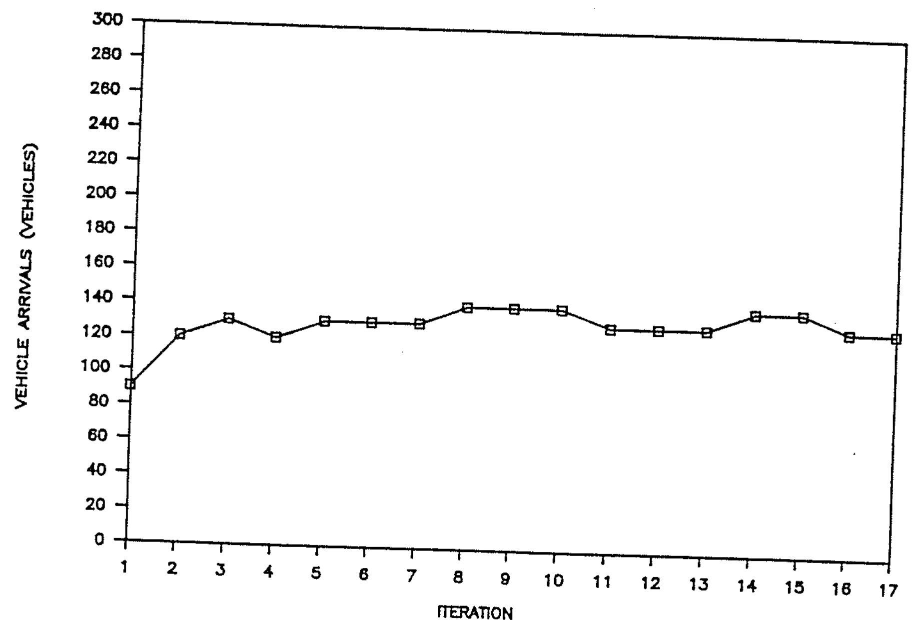
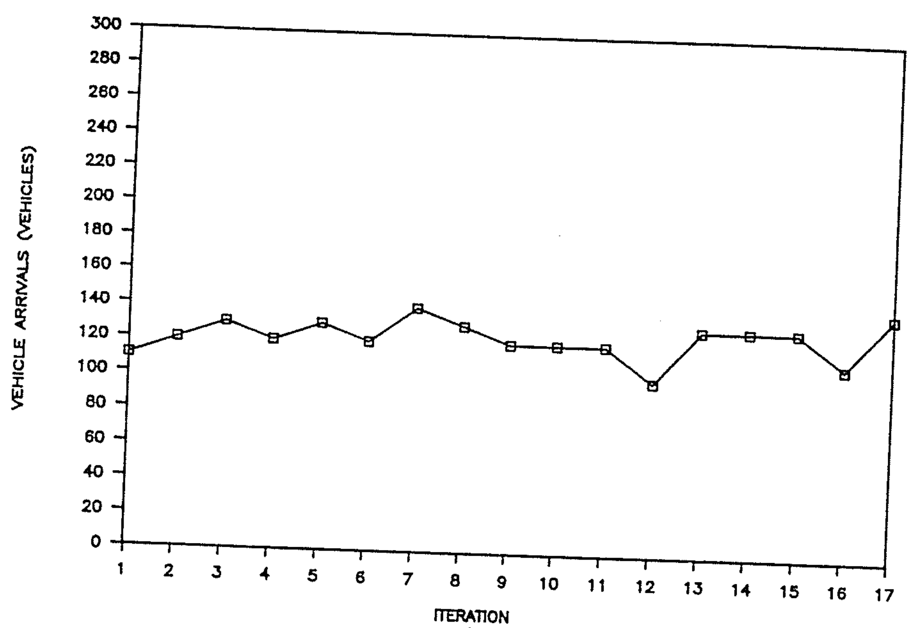


FIGURE 19 - ARRIVALS AT LINK 204 AS A FUNCTION OF ITERATION. BASE NETWORK 1. (A) TIME INTERVAL 3. (B) TIME INTERVAL 7



(A)



(B)

FIGURE 20 -ARRIVALS AT LINK 204 AS A FUNCTION OF ITERATION. BASE NETWORK 2. (A) TIME INTERVAL 3. (B) TIME INTERVAL 7

6.5 - Summary of the Base Networks

It is apparent that, due to the various interactions, traffic control and capacity restraints, the vehicle flow behavior on links does not necessarily reflect the nature of demand at the origins. The consistency of the amplitudes shown by the cycles of demand was not reflected in the delay measure or in arrivals at link 204. Observations of arrivals at links, or of system behavior as indicated by delay, may not be enough to establish the way in which demand varies. Furthermore, in more realistic networks with greater origin destination pairs, non-identical work start times at the destinations, and much more traffic control, it is possible that the greater degree of interaction would result in field observations completely unreflective of the nature of departures with time at the origin.

The variation of delay and arrivals at link 204, in base network 1, and the variation of arrivals at link 204 although not as cyclic, were still of significant amplitude. They also, for the most part, fluctuated within a band. A greater range of iterations would have to be studied in greater depth to understand the behavior of the system. If the system was strongly cyclic with consistent amplitudes only the iterations of a single cycle would have to be studied.

Base network 2 with two desired arrival times showed much smaller percent differences in its variations of demand, delay, and arrivals on link 204 than those of base network 1. It seems that the range of variation is related to the levels of congestion in the system. The variation of delay and arrivals at link 204 was within tighter bands than that shown by the variations of demand for both networks.

Now that system behavior and the behavior of demand have been analyzed, it is desirable to consider the possibility of using CONTRAM in a departure time selection model to analyze various network improvements. This will be done in the next section by considering a variety of changes and improvements to the network.

7.0 - CONGESTION REDUCING TECHNIQUES

Like the single origin-destination problem, it is important to determine how the departure time selection model using CONTRAM to estimate travel times would model changes to the system. In this way it can be determined if the model provides reasonable results. To this end changes to the base network aimed at reducing congestion to improve service were considered. An examination of the output from the various iterations of the two base networks showed that base network 1 was the most critically loaded and oversaturated. Changes were concentrated on this network. Three additional runs were made for network 1. With a single desired arrival time, a run was made with capacity increases, and another studied the effects of adopting flexible work hours. The adoption of two flexible work start time periods, with the same split in volume as base network 2, was also considered. A summary of the relevant differences between the five networks is summarized in Table 6.

7.1 Effects of Increased Capacities on Base Network 1

As displayed in Table 6, in order to study the effects of increased capacities on base network one, the saturation flow of link 304, link 204, and link 215 were increased from

600 to 800 vehicles per hour, from 1500 to 3000 veh/hr and from 1600 to 3000 veh/hr, respectively. The latter two changes might represent an additional lane, while the first change at link 304 could represent increased lane width, or improved geometry or sight distance for the merging traffic. These links were modified because the CONTRAM model predicted that they would be consistently oversaturated in the base network in most time intervals.

TABLE 6 - RUNS MADE WITH THE MULTIPLE ORIGIN DESTINATION NETWORKS

Run	Desired Arrival Time	Link	Sat. Flow
Base 1	8:00 am	204 215 304	1500 1600 600
Alternative 1 Inc. Cap.	8:00 am	204 215 304	3000 3000 800
Alternative 2 Flex. 1	7:40-8:10 am	204 215 304	1500 1600 600
Base 2	7:30 am & 8:00 am	204 215 304	1500 1600 600
Alternative 3 Flex. 2	7:30-7:50 am & 8:00-8:20 am	204 215 304	1500 1600 600

Sat. Flow - saturation flow (veh/hr)
Inc. Cap. - increased capacities
Flex. - flexible desired arrival time
Inc. Speed- increase speed.

As in base network 1, the demand for most of the various O-D pairs for all of the above runs resulted in cyclic variation of demand. Like the base network, fringe time intervals, that is those at the beginning and end of the time frame of study, varied more randomly than the peak time intervals. Figure 21 compares the average departure rate distributions of base network 1 and the network with increased capacities for origin destination pair 1. The peak demands are higher with the higher capacities, resulting in a narrower distribution of the average departures over time. This is expected given the higher capacities. The time intervals of peak demand for the most part still shifted over similar ranges during the iterations as in base network 1, although the peak time interval of O-D pair 4 shifted only between 5 and 6. For the network with greater capacities, however, volumes in the later time intervals tended to be higher. The peaks also tended to occur in later time intervals during more iterations than in earlier time intervals. These two factors lead to the average distribution shown. These results are also true for comparisons of origin-destination pairs 2 and 4. This is consistent with the results of the single origin-destination problem.

It is important to emphasize again that the trends shown by the distributions of average values of the relevant

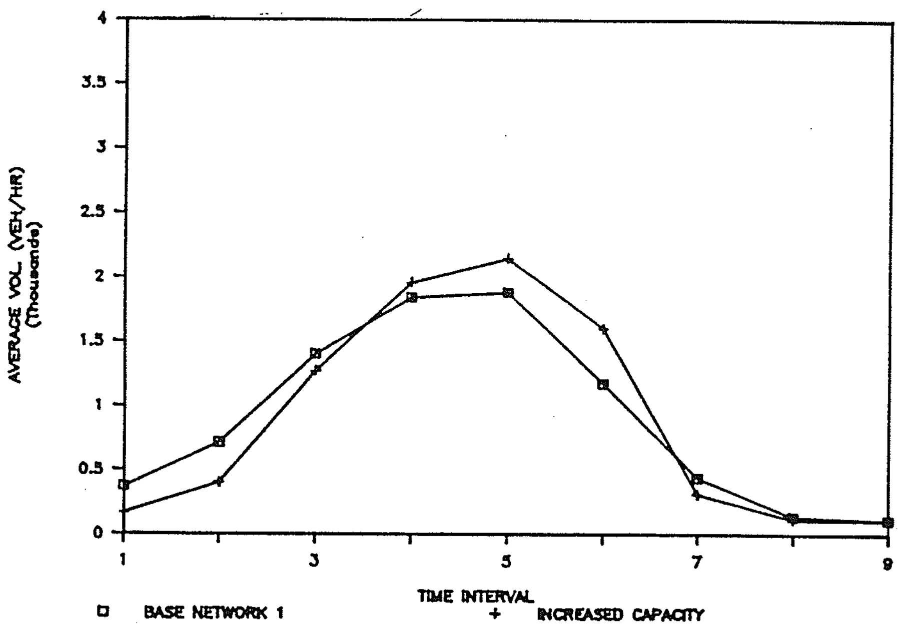


FIGURE 21 - AVERAGE DISTRIBUTION OF DEPARTURES
THE EFFECTS OF INCREASED CAPACITY
O-D PAIR 1

parameters were not as evident when examining the distributions from iteration to iteration. An examination of results, iteration by iteration, showed that the peak demands for the network with increased capacities were not consistently greater than those of the base case, rather they tended to be greater in most cases. In fact, the trend was not clearly evident until the distribution of averages was plotted.

Results for O-D pairs 3 and 5 showed that there was a strong degree of repeatability of the results obtained. For both links, the distribution of the average departure rates over the time intervals for the base case and the increased capacity network are almost indistinguishable. This is a reasonable result, as these two O-D pairs are not as directly affected by the changes, as they use links moving in the opposite direction, and therefore do not utilize links 204, 215, and 304.

For comparison with the base network the systems total delay was plotted over the iterations performed. The average delay was 130.1, significantly lower than the base network, indicating an improvement of traffic conditions. The plot of delay versus iteration in Figure 22 was more cyclic, suggesting that the level of congestion may have an effect on the consistency of the cycle amplitude.

Finally, the vehicle arrivals on link 204 were

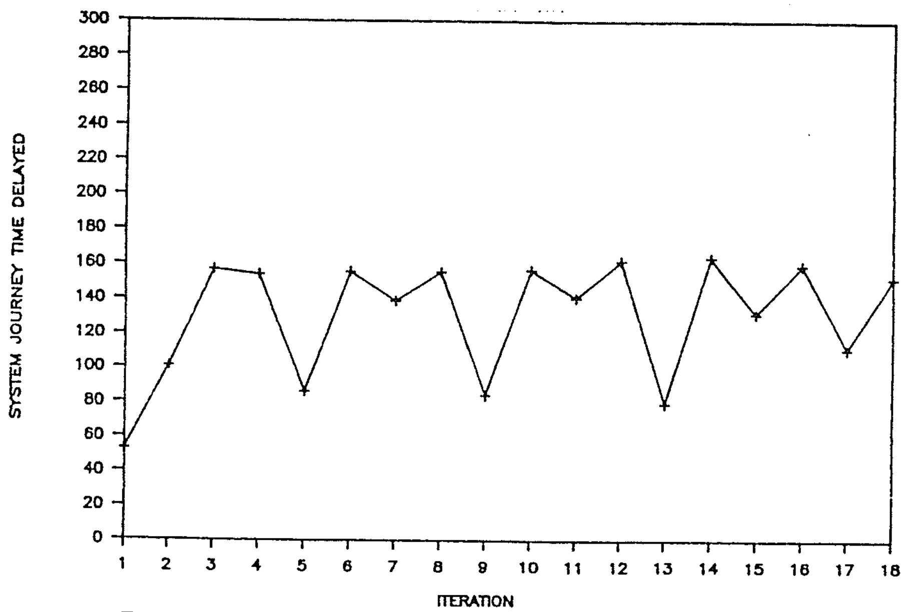


FIGURE 22 - DELAY AS A FUNCTION OF ITERATION
THE EFFECTS OF INCREASED CAPACITY

considered. Figure 23 shows that the increased capacity of link 204 attracted much higher volumes. This element of route selection is not present in the single origin-destination problem. One hypothesis resulting from this observation is that the element of route selection might lower the degree of shift of demand to later times than would be expected if there was only one route. Greater volumes are attracted from other routes and therefore less capacity is available for vehicles that might want to shift departure time.

7.2 - Adoption of A Flexible Work Start Time Plan

For the initial investigation of the effects of adopting a single flexible work start time plan for the network, the same work start time band was adopted for all vehicles in all origin destination pairs. As indicated in Table 5, a 30 minute band was used between 7:40 pm and 8:10 pm. Capacities of all links remained the same as in base network 1.

The resulting demand patterns settled again rather quickly into cyclic behavior. Figure 24 shows the comparisons of the average demand distributions for O-D pairs 1 and 3. Similarly, every origin destination pair has shown that over the iterations demand spreads over more time intervals, and the averages are more uniform. There is

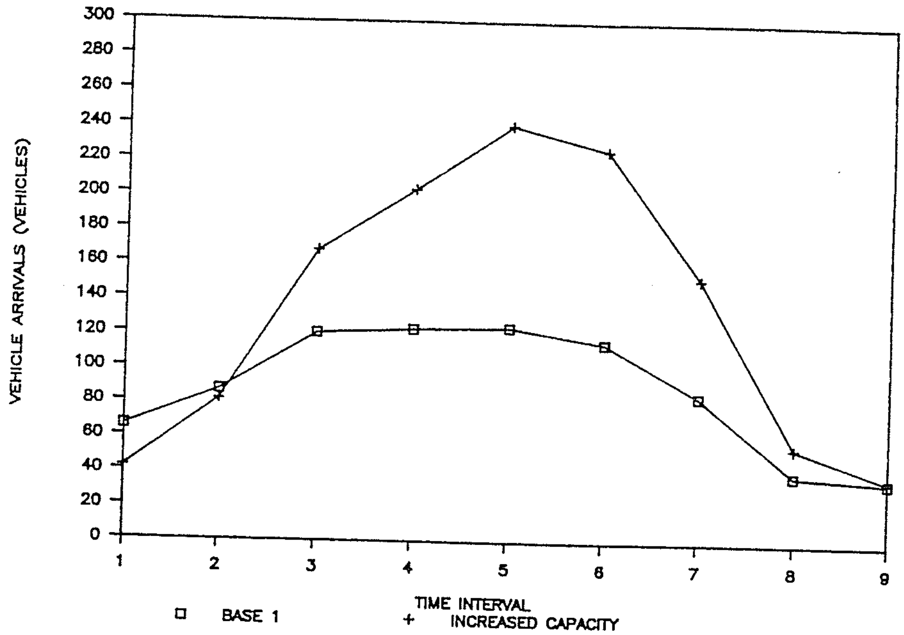
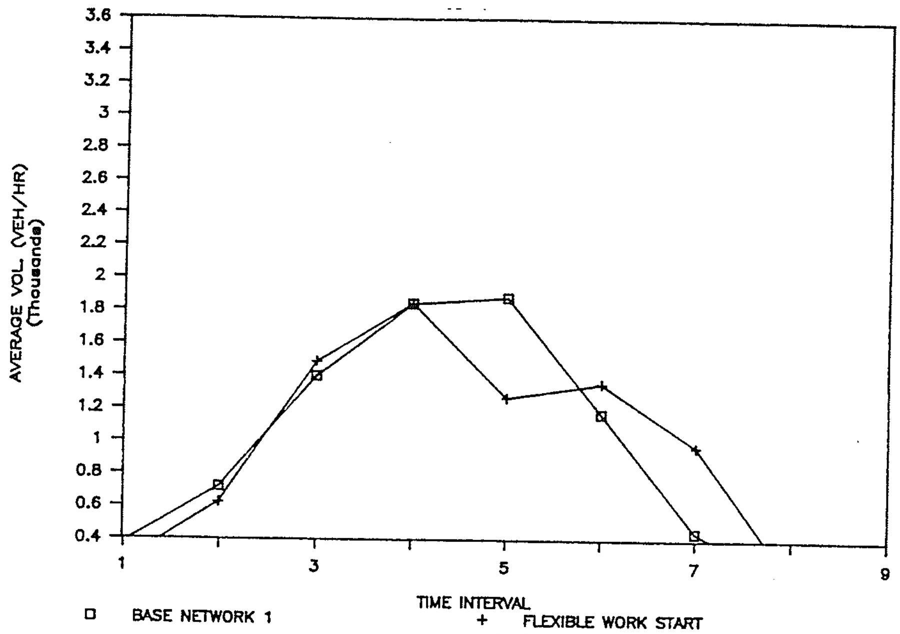
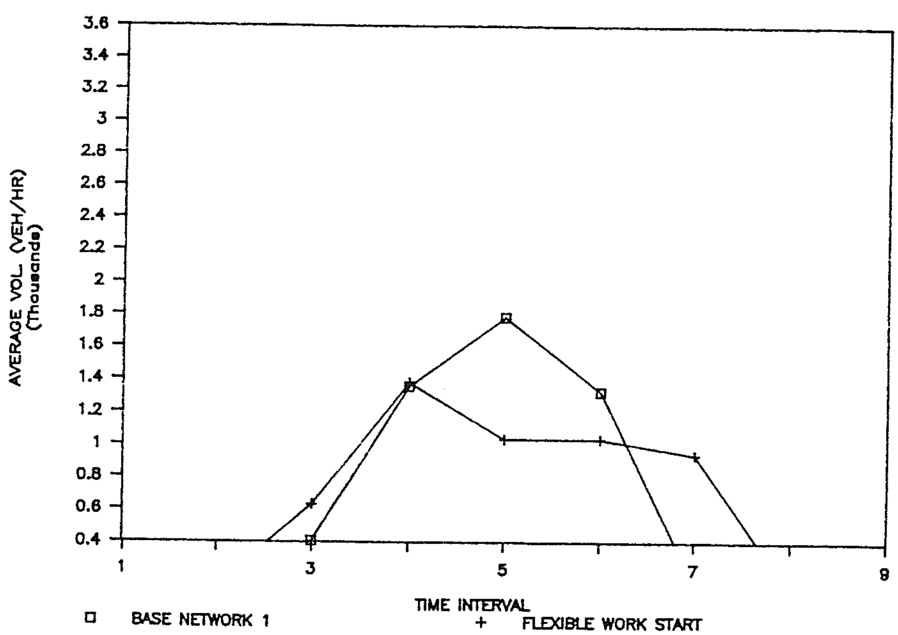


FIGURE 23 - AVERAGE DISTRIBUTION OF ARRIVALS AT LINK 204. COMPARISON OF BASE NETWORK 1 AND ALTERNATIVE 1.



(A)



(B)

FIGURE 24 - AVERAGE DISTRIBUTION OF DEPARTURES. COMPARISON OF BASE NETWORK 1 AND ALTERNATIVE 2. (A) O-D PAIR 1. (B) O-D PAIR 3

relatively significantly greater peaking from iteration to iteration for the flexible work start plan than is reflected by the distribution of the average demands. However, after examining a sample of consecutive iterations the trend of a wider distribution of demand over time with lower peaks was still consistently evident. The system totals of delay for this run, alternative 2, resulted in lower delay than both base network 1 and alternative 1 with an average of 109.7 vehicle hours. The cycle amplitude of delay was not as consistent as the cycle of variation of the departure rates.

Comparison of the arrivals on link 204 between base network 1 and the single flexible work start time showed that the average distribution of arrivals across the time intervals were very similar, suggesting that route assignment in the two situations were not that different. It is hypothesized that this is in part due to the capacity constraints upstream. The flexible work start time allows vehicles to leave over a greater range of departure times, spreading the demand out. However, the links upstream of link 204 are major bottlenecks with arrival rates greater than the capacities in both networks. Output from the links upstream of 204 therefore leave at a rate equal to the capacity in either case.

7.3 - Two Flexible Work Start Time Periods

Two flexible work start time periods from 7:30 am to 7:50 am and 8:00 am to 8:20 am were adopted and simulated, and compared to base network 2. Similar to the single, 30 minute, flexible work start time period, demand from iteration to iteration was more spread out over the time intervals relative to the network for base case 2. If vehicle departures in each work start time period are analyzed separately, the peak time intervals shifted over a wider range than in base network 2.

Figure 25 shows that the average distributions of vehicle departures for vehicles in each work start time period for a given O-D pair are not nearly as similar to each other as they were in base network 2, with two rigid times of arrival. The wider distributions of departures in each work start time category has resulted in more overlap between the two. It is likely that later vehicles from the first group are still in the network when the first vehicles from the second group start entering the network, so there is more interaction between the two.

The percent difference in the variation of delay from iteration to iteration for alternative 4 is quite small, almost negligible, for the network with two flexible work start time periods. The average for base network 2 was 80.78 veh-hrs, and the average for alternative 4 was 70.8 veh-hrs.

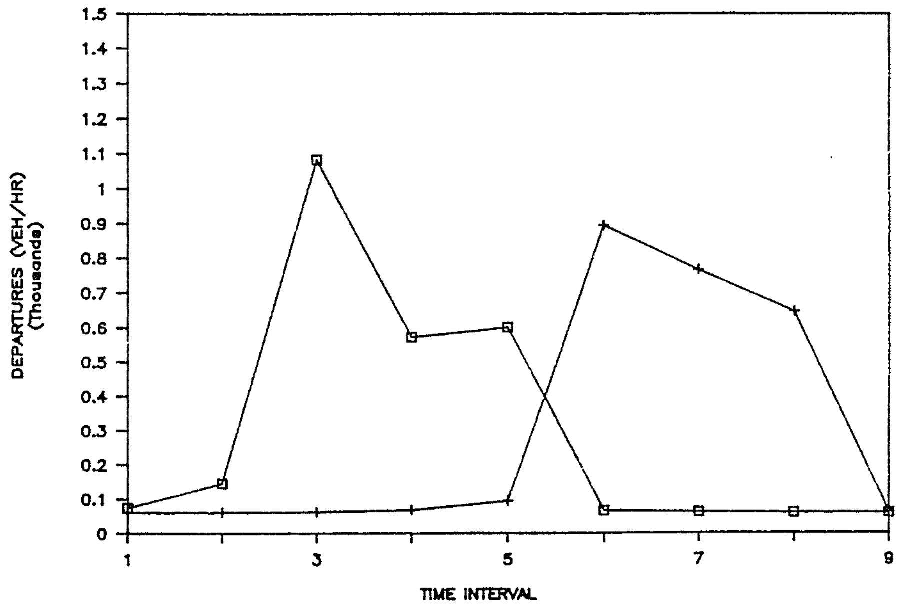


FIGURE 25 - AVERAGE DISTRIBUTION OF DEPARTURES. O-D PAIR 3. COMPARISON OF DEPARTURES FOR WORK START TIME PERIODS 1 AND 2.

Examination of the network showed much lower degrees of saturation throughout the network, and it is likely that commuters may alter their departure times more freely without effecting congestion as much.

The average distribution of arrivals at link 204 over the time intervals for alternative 3 is quite different than the average distribution of base network 2. This is in contrast to the comparison made in the previous section between base network 1 and alternative 2, whose average distributions were quite similar. Links upstream of link 204 for base network 2 and alternative 3 were consistently undersaturated, below 80%, for most of the iterations, and therefore the arrivals at link 204 were more reflective of the behavior of the input demands.

7.4 - Summary of the Changes to the Base Networks

After studying the five networks at various levels, it became apparent that many iterations of the CONTRAM/departure time selection model might have to be performed. If cycle amplitudes are consistent, then detailed study of the network behavior can then be limited to a sample of successive iterations. If on the other hand behavior is more irregular from iteration to iteration, more analysis will have to be carried out over a greater number of iterations.

Despite the greater inconsistency of system behavior in some of the networks an effective comparison between the five networks was still possible. As in the single origin-destination pair the general behavior of the network was still consistent with what is expected. Increased capacities resulted in greater peak demands shifted toward later times, and decreased delays. Flexible work hours spread the demand over greater time, and also decreased delays.

8.0 - OTHER SENSITIVITY ANALYSIS

The study of various congestion reducing alternatives in the previous section produced reasonable and explainable results. The research was therefore extended to other sensitivity analyses. The primary emphasis of this chapter is the consideration of various volume increases and is considered in two ways:

1) through direct increases in volume of some of the origin-destination pairs considered.

2) through the increase of competition for use of links by the addition of another origin-destination pair.

Also considered is the effect of speed increases on some of the links in the network.

8.1 - The Effects of Volume Increases and Increased Competition.

To study the effects of increased volumes of vehicles three additional runs of the CONTRAM/departure time selection model were carried out. Various volume increases of base network 1 were made, maintaining the same single desired arrival time. The resulting demand behaviors were compared to each other and the results from the base network. First of all, the volume of vehicles on O-D pairs 4 and 5 were doubled. In other runs a sixth origin-destination pair was added: O-D pair 5004 to 9002, as coded in Figure 13, was given a total demand of 255 vehicles in one run, and 310 in another. Three additional runs were made. Table 7 outlines the relevant differences of the various runs. O-D pairs 1,2 and 3 remain unchanged throughout the runs, and therefore are not listed in the table.

Similar to previous results, an equilibrium solution was not reached and departure rates varied cyclically. From the base network to the final network, with 4200 total vehicles, there were generally two types of O-D pairs, those directly affected by the changes, and those indirectly. The indirectly affected O-D pairs are those to which no change in volumes occurred, but whose vehicles would have increased competition with the additional vehicles in the network derived from the other O-D pairs. O-D pairs 1,2 and 3, were indirectly affected for all the runs.

Although the increased volumes of demand did tend to result in a general increase in the average departure rates in all time intervals, the increase was not symmetric. The earlier time intervals tended to share a greater portion of the extra volume. The time intervals of peak demand shifted during the iterations over a greater range of time intervals. Figure 26 shows, for example, how the demand has resulted in a greater increase in the earlier time intervals for O-D

TABLE 7. VARIOUS CHANGES TO EXAMINE THE EFFECTS OF INCREASED NETWORK VOLUME

Network	O-D Pair	Demand (Veh.)	Total Network Demand (Veh.)
Base Network 1	4	293	3200
	5	188	
	6	Not Modelled	
Sensitivity Analysis 1			
Increased Competition	4	293	3460
	5	188	
	6	255	
Sensitivity Analysis 2			
Increased Volumes to O-D pairs 4 and 5	4	586	3680
	5	376	
	6	Not Modelled	
Sensitivity Analysis 3			
Increased Volumes to O-D pairs 4,5 and 6	4	586	4200
	5	376	
	6	510	

O-D - Origin-Destination
Veh. - Vehicles

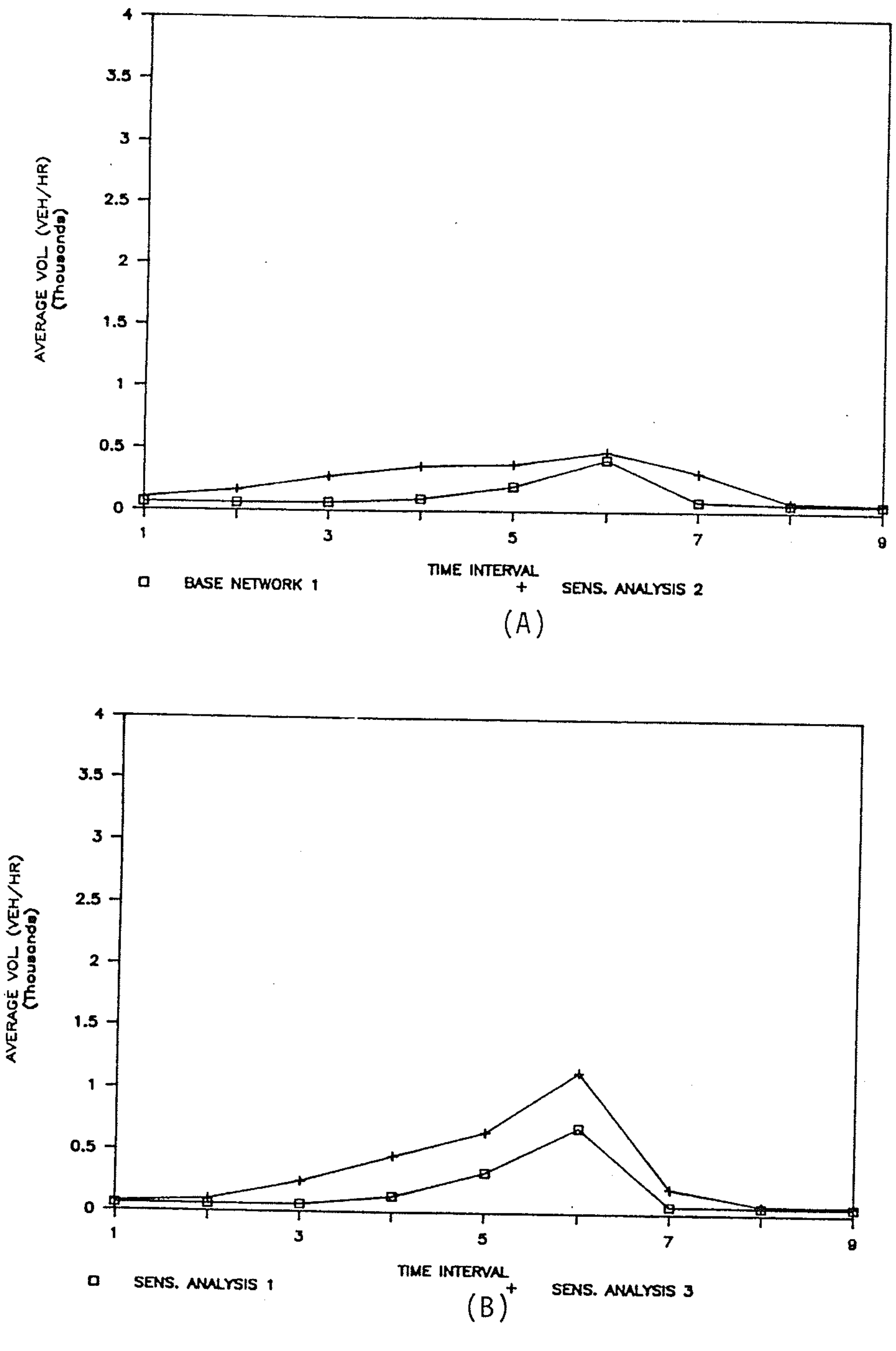


FIGURE 26 - AVERAGE DISTRIBUTION OF DEPARTURES THE EFFECTS OF INCREASED VOLUMES. (A) O-D PAIR 5. (B) O-D PAIR 6.

pairs 5 and 6. These observations were consistent for all O-D pairs whose total demands were increased.

The effects on the indirectly affected origin-destination pairs were not clear when compared from one change to the next. The changes in the average distributions were not consistent or that apparent. For example, with increased competition in sensitivity run 1, the average departure distribution of O-D pair 1, shown in Figure 27, is not that different from the base network. Similar observations hold for the other indirectly affected O-D pairs when the average distributions are compared from one change to the next.

Origin-destination pairs 1,2, and 3 have constant volume for all the networks. The changes to the demand distributions for these pairs can be followed and compared over all the changes made, as a function of increasing network volume. Although the changes in the departure distributions were much more apparent after this is done, there was still no consistent trends observable in the results.

Figure 28 superimposes the average distributions for base network 1 and sensitivity analysis 3, for O-D pairs 1 and 3 as examples. The average departure distribution of origin-destination pair 1 does show a trend to increasing spread of the demand, and a shift of the peak demand to earlier time intervals, when volumes increase. However,

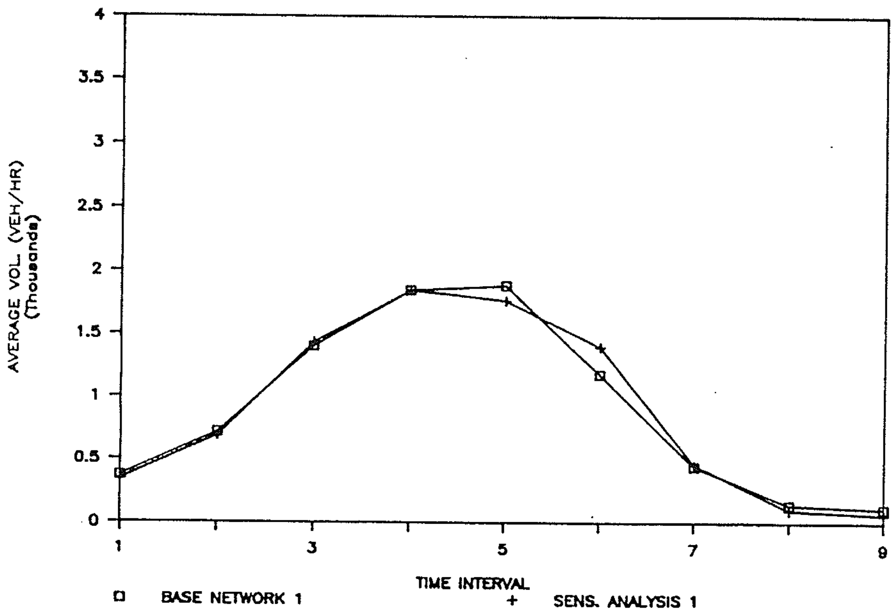
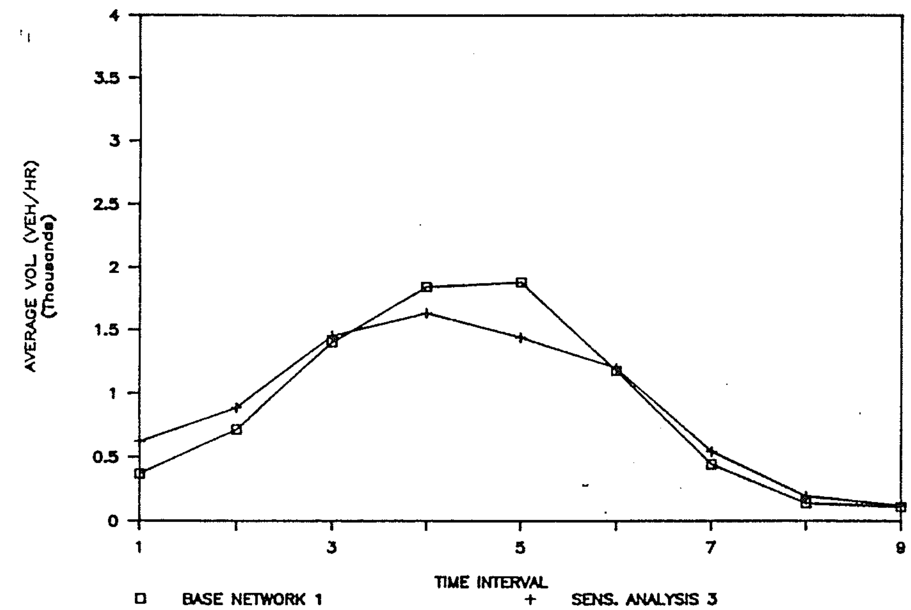
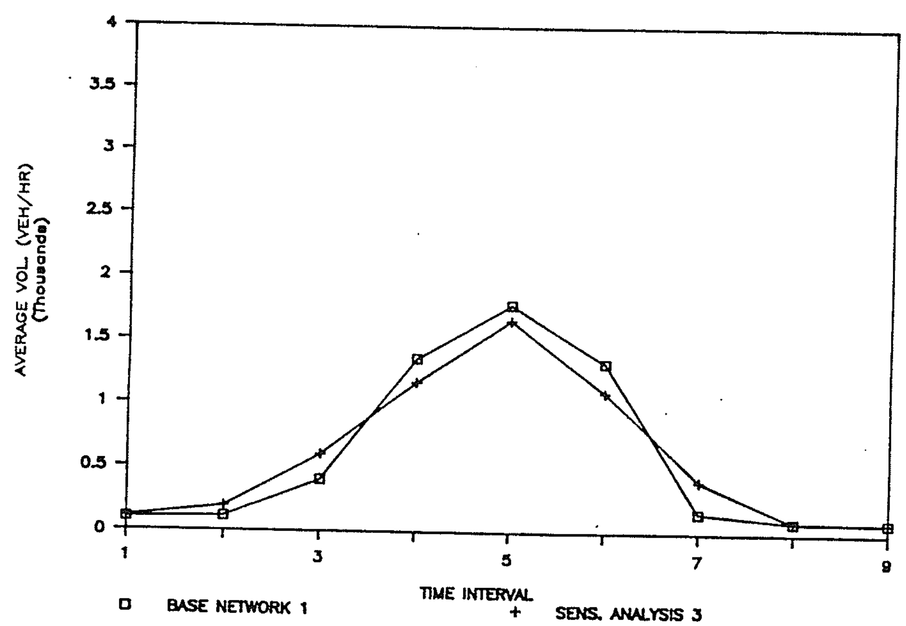


FIGURE 27 - AVERAGE DISTRIBUTION OF DEPARTURES THE EFFECTS OF INCREASED VOLUMES OF OTHER O-D PAIRS ON O-D PAIR 1.



(A)



(B)

FIGURE 28 - AVERAGE DISTRIBUTION OF DEPARTURES THE EFFECTS OF INCREASED NETWORK VOLUMES ON O-D PAIRS 1 (A), AND 3 (B).

departures of O-D pair 3 seem to have spread out more evenly over all the time intervals symmetrically. The departure rates of the peak time intervals have lowered, and have increased equally in fringe time intervals on either side of the peak. Similar observations as those made of O-D pair 3 were made of O-D pair 2.

It is possible to hypothesize that an increase in network volume is similar to a decrease in capacity. Results for O-D pair 1 support this. An increase in network volume had a reverse effect on the shift in demand that the increased capacity analysis in chapter 7 had. However, the results of O-D pairs 2 and 3 do not support this hypothesis as well.

8.2 - The Effects of Increased Speeds

Since the cost model is based on the time of arrival and the total travel time, it is anticipated that increased travel speed in the network could have a significant effect on the nature of departure time selection. To investigate this possibility, the free flow travel time on links 204, 215, and 304 of base network 1, were increased. This raised their free flow speeds from 48, 45, and 43 kilometers per hour respectively to 60 kilometers per hour.

The results showed that the changes in speed on these links had very little effect on the average departure rate distributions for any of the origin-destination pairs studied. When studied further, it was also found that the increase in free flow speed on link 204 did not change the resulting route selection either. As shown in Figure 29, the average arrival distribution was also not very different from that of the base network.

The reasons for this are clear. The factors that lead to these results are the size of the network, the level of congestion, and the length of the time interval. The change in free flow speeds, result in free flow travel times that are 15 to 20 seconds shorter. However, the level of congestion in the network results in delay being the most significant part of the travel time. The average total travel time, in vehicle-hours, is only improved by about 3%, not enough to result in significant changes in route selection.

The links and total network sizes are small in terms of their free flow travel time relative to the size of the time intervals. A small change in travel time, in the order of seconds, is not going to result in a shift of 10 minutes or more in departure time selection. CONTRAM Version 4 can model a maximum of 13 time intervals. As it becomes necessary to examine longer time periods, for example due to longer travel times through a network, it may be necessary to

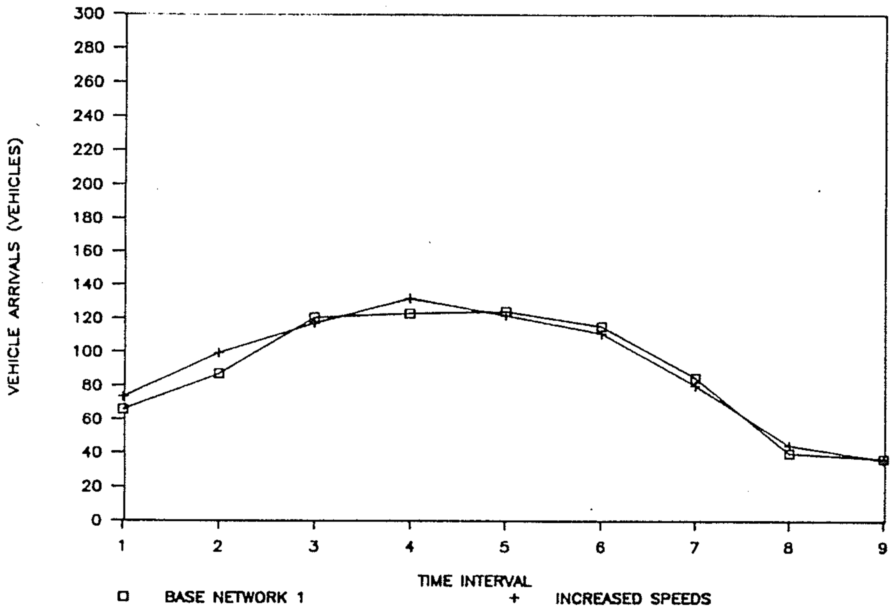


FIGURE 29 - AVERAGE DISTRIBUTION OF ARRIVALS ON LINK 204: COMPARISON OF BASE NETWORK 1 AND THE NETWORK WITH INCREASED SPEEDS

decrease the refinement of the time intervals. Rather than increasing the total amount of time interval, the time intervals would have to be larger. This could result in missing the effects of certain departure time decisions that are being made.

9.0 - DISCUSSION

The issue of sequential versus simultaneous selection of routes and departure times is important. It is uncertain which is a more correct reflection of commuter behavior. In the case of sequential modelling the nature of CONTRAM limited this research to examining departure time selection first and then determining the equilibrium route selection under each distribution of demand for each iteration. Using other techniques it might be possible to consider searching for an equilibrium solution of departure time distributions under fixed route assignments. Thus there are three possibilities, simultaneous selection, route selection under a fixed distribution of demand in each iteration, and departure time selection under fixed route assignment in each iteration. Whether iterative models using any of the techniques result in similar solutions or the same equilibrium solution is uncertain. This issue would be an interesting topic for further research.

Although equilibrium solutions did occur in the single origin-destination problems, all the multiple origin-destination problem resulted in cyclic solutions. Cycle amplitudes of delay and arrivals on a sample link, were not as consistent as the amplitudes of the departure rates, but still varied within a band. Whether an equilibrium solution exists is uncertain. It is possible that the proposed method may be missing it. On the other hand cyclic behavior may be more realistic. A survey of commuters who travel to work each morning by Alfa and Eden (1988) showed significant day to day variation in the time of departure for many of the commuters sampled.

It would be useful to have data of vehicle volumes on roadway sections in 10 or 15 minute time intervals over many consecutive days in order to understand the nature of changes in traffic flow with time. Communication with cities such as Toronto, Vancouver, Calgary, Edmonton, and Winnipeg revealed that this type of data is hard to obtain. Both the cities of Edmonton and Winnipeg were able to supply such counts, but only for five consecutive week days. Calgary provided a two week count, but only for one location. This length of observation made it difficult to establish any trends in variation. Over the periods of observation given, demand was fairly regular. Whether this is true on a week to week basis was impossible to determine. Furthermore, as discussed earlier, behavior of traffic flow may not reflect the behavior of demand.

The research carried out for the completion of this thesis involved the development of a model to work in conjunction with CONTRAM. The model was based on earlier work by Alfa and Minh (1979) with modifications to their stochastic approach. Similarly the cost function was of a common form used by many researchers. The coefficients used, though based on previous research, should only be interpreted as a hypothetical situation. This was done in order that model development and preliminary investigation could proceed. Before this research is extended to any real problems calibration of the joint model is necessary. This would include determination of the cost coefficients for Equation 1, and the "ß" term in Equation 4.

The departure time selection model, as discussed earlier, was a deterministic simplification of the stochastic model developed by Alfa and Minh (1979). The deterministic assumptions are made with reference to two issues. First, it is assumed that the commuters know exactly what the cost is in every time interval, and secondly that the commuters evaluate the cost in the same way all the time and exactly according to the cost function. These assumptions are obviously simplifications and may not be entirely realistic. It is felt, however, that the model of Chapter 4 is a reasonable approximation of stochastic effects. Although it was assumed the costs were deterministic, not all vehicles changed to the lowest cost time interval according to the model. The volume of vehicles changing departure times to other time intervals was proportional to the deterministic costs. The impacts of the assumptions are presently undetermined.

Another simplification was the use of the centroid of the time interval as average departure time in each time interval. This was done because all CONTRAM outputs is the average speed for all vehicles departing in a time interval for each O-D pair. This resulted in the use of the average cost for all vehicles departing in a time interval. There could be a wide distribution of speeds incurred over all the packets of an O-D pair departing in each time interval. However, it was not possible to determine this from the output of the version of CONTRAM that was used in this research.

10.0 - CONCLUSION

Results of the investigation have shown that using CONTRAM together with the departure time selection model iteratively has provided reasonable results. The results obtained include:

1. Increased capacities shifted demand to later time intervals, and increased the total demand in the peak time intervals.

2. Increased volumes in the network resulted in the earlier time intervals for the total network demand having a more than proportionate increase in demand than later time intervals.

3. The adoption of a flexible work start time plan spread the demand out more uniformly over greater time intervals than a rigid work start time plan.

These results are consistent with predictions from other models of single origin-destination pairs. The element of route selection may lessen certain impacts. For example increased capacities of some routes, will attract greater volumes and therefore lessen the shift of demand to later time intervals.

The investigation of the effects of increased speeds suggested that the ability of CONTRAM to assess certain issues when adapted to the departure time selection model might be linked to some relationship between the total travel times in the network, the length of the time interval, and the magnitude of changes in travel times being considered. In the research in this paper the free flow travel time was changed, but had no significant effects on the results. The change resulted in a small reduction in free flow travel time relative to the length of the time interval, and resulting demand distributions were not affected. A network with increased time frame of study requires larger time intervals because of CONTRAM's fixed maximum number of time intervals. Significant reductions in free flow travel time may not have a significant effect on the model if the time intervals are too large, which may result in effects in the real problem being unaccounted for.

Despite certain concerns, adapting CONTRAM to the problem of solving for the distribution of demand with time provided reasonable results. By using CONTRAM with the hypothetical network and uncalibrated cost model, and the departure time selection model, logical quantitative comparisons between alternative networks with multiple origins and destinations were made. Restraints on the number of time intervals may limit application of CONTRAM to such a problem to a more microscopic planning level, rather than broader planning at city wide levels. Possible research involving trial application of the CONTRAM/departure time selection model to real problems is worth while. Before this could proceed the cost model and departure time selection model, for which the coefficients were assumed in this research, would have to be calibrated.

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APPENDIX A

THE COMPUTER PROGRAM AND PROCESS

The overall process:

Following is an outline of the entire departure time selection modelling process including the link with CONTRAM which was used for the estimation of travel times under a given demand distribution. The variable "ITER" represents the input number of desired iterations of the process.
Step 1: For iterations 1 to ITER:

Step 2:
Batch file "CONTRAM.bat:" is executed.

Step 3A:
"CONTRAM.bat" executes the CONTRAM package, "CONTRAM4.exe", which reads three input files: the demand files, the network coding files, and a control file which tells CONTRAM the types of runs being made and the output expected from it.

Step 3B:
"CONTRAM4.exe" outputs a file called "RESULTS", which contains various resulting network measures such as volumes on routes, degrees of saturation, average speeds.

Step 4A:
The departure time selection model "AUTOMAT3" is executed by the "CONTRAM.bat" batch file.

Step 4B:
The "RESULTS" file is read, and the model uses the results to obtain a new distribution of demand for each origin destination pair, and each desired arrival time.

Step 4C:
The batch file "DUP.bat" to be used in step 4 is edited,updating it to the present iteration number.

Step 4D:
If iteration=ITER then dummy file "LAST" is created otherwise the file "ITER",which identifies the iteration number, is edited to the present iteration number.

Step 5A:

"CONTRAM.bat" executes a second batch file, "DUP.bat", which copies the "RESULTS" file and the demand file to another file with a new name which identifies them by the iteration number, so they will not be overwritten by subsequent runs.

Step 5B:

"Dup.bat" considers dummy file "LAST", if it exists then the run is ended, otherwise go back to Step 1 and repeat all steps.

Following is a listing of the "CONTRAM.BAT" batch file. Line 2 ensures that the dummy file "Last" of a previous run is not on the system otherwise the run will stop after the first iteration. Line 3 calls up the CONTRAM software and calls an input file, "input", which automatically responds to the prompt statements of "CONTRAM.exe". Line 4 initiates the departure time selection model, "AUTOMAT3.bat" and returns to dos after completion of the run.

```
1. echo off
2. IF EXIST LAST DEL LAST
3. contram4.exe <c:input
4. gwbasic automat3 <C:SYST
5. DUP
```

Line 5 of the above initiates a second batch file, "DUP.BAT". Following is a listing of that program. Rvolxx, rvcosxx, and rvdemxx, are the CONTRAM output file, the cost files, and the demand file, respectively, for each iteration, xx. "AUTOMAT3", edits the xx extension after each iteration.

Line 5 of the following starts the next iteration by initiating "CONTRAM.BAT"

```
1. COPY B:RESULTS c:rvol21
2. COPY c:cost c:rvcos21
3. COPY c:demand c:rvdem21
4. if exist last goto nnnn
5. CONTRAM
6. :nnnn
```

The departure time selection model

The following outlines the process of the program "AUTOMAT3", step 3 above, which includes the departure time selection model and other file editing functions. The variables OD, WST, and TI represent the total number of origin-destination pairs, desired arrival times, and time intervals respectively.

Step 1:
Output from "CONTRAM4.exe", in the output file "RESULTS", is searched until the character string that identifies the output corresponding to average speeds of travel for each origin-destination pair is located.

Step 2: For origin-destination pair 1 to OD
Step 3: For time interval 1 to TI

Step 4:
The average speed of travel for the total trip for vehicles leaving in the time interval is read from the "RESULTS" file.

Step 5:
The average travel times are calculated by dividing the straight line distance between the origin and destination by the average speeds obtained in Step 2

Step 6: Next time interval (repeat steps 4 & 5)
Step 7: Next Origin destination Pair (repeat steps 3-6)

Step 8: For origin-destination pair 1 to OD
Step 9: For desired arrival time 1 to WST
Step 10: For time interval 1 to TI

Step 11:
The cost incurred by vehicles leaving in the time interval is calculated using the travel times obtained in Step 4 to determine the times of arrival and by applying Equation 1.

Step 12: Next time interval (repeat step 11)

Step 13: For time interval 1 to TI

Step 14:
The expected reduction in cost associated with shifting to a time interval from each of the other time intervals is determined using the costs obtained in Step 11, and applying Equation 2.

Step 15:
All the expected reductions in cost of the time interval calculated in Step 14 are totalled.

Step 16: Next time interval (repeat steps 14 & 15).

Step 17:
The minimum cost time interval (for the present O-D pair and present desired arrival time) is determined.

Step 18:
By applications of Equation 5, a new volume of departures for each time interval is determined.

Step 19:
If the any of the new volumes are less than a packet size their volumes are raised to a packet size and the corresponding increase made up subtracting the changes from the remaining time intervals proportional to their volumes.

Step 20: Next desired time of arrival (repeat steps 10-19).

Step 21: Next origin-destination pair (repeat steps 9-20)

Step 22:

The input demand files for "CONTRAM4.exe" are edited by writing the newly obtained demand to the old files.

Step 23:
The file "ITER", which keeps track of the present iteration number is edited, increasing the iteration by 1.

Step 24:
"DUP.bat" is edited as outlined in the previous section.

Listing of "AUTOMAT3.bas"

```
10 REM ********* PROGRAM THAT DETERMINES THE TEMPORAL DISTRIBUTION *********
20 REM ******** OR PEAK TRAFFIC DEMAND BASED ON OUTPUT FROM CONTRAM ********
30 REM ***** AND EDITS THE INPUT FOR CONTRAM FOR SUCCESSIVE ITERATIONS *****
40 REM
50 OD=6:L(1)=3:L(2)=2.3:L(3)=2.7:L(4)=2.3:L(5)=1:L(6)=2:WST=1:T=10
60 DIM V(10,10,10),TT(10,10,10),TI(10),C(10,10,10),CMIN(10,10),V2(10,10,10),S
,10,10),DAT(2),Q(10,10,10)
70 OPEN "i",1,"b:RESULTS"
80 REM
90 REM **** LINE 130 TO 330 READS THE DATA FROM CONTRAM'S OUTPUT ***
100 REM *** UNTIL IT FINDS THE SPEEDS FOR EACH TIME INTERVAL FOR ***
110 REM ************* EACH OD PAIR AND WORK START TIME *************
120 REM
130 FOR I=1 TO 9999
140 LINE INPUT #1, A$
150 REM
160 REM ***** THE CHARACTER STRING IN LINE 60 PRECEDES *****
170 REM ***** THE OUPUT OF AVG. STRAIGHT LINE SPEED IN *****
180 REM *************** IN CONTRAM'S OUTPUT ****************
190 REM
200 IF A$="  ORIG  DEST  VEH.  LIN.     AVERAGE  STRAIGHT  LINE  SPEED (KMS/H
FOR  PACKETS  ENTERING  IN  TIME INTERVAL :" THEN I=9999
210 NEXT
220 INPUT #1, A$, B$, D$
230 FOR I=1 TO OD
235 FOR H=1 TO WST
240 INPUT #1, B, BB, BBB, E
260 FOR J=1 TO T-1
270 IF H=1 THEN INPUT #1, S(H,I,J) ELSE S(H,I,J)=S(1,I,J)
273 REM IF H>1 THEN INPUT #1, SS(T)
280 PRINT S(H,I,J)
290 REM
300 REM **** TRAVEL TIME IS CALCULATED *****
310 REM
320 IF S(H,I,J)>0 THEN TT(H,I,J)=(L(I)/S(H,I,J))*3600  ELSE TT(H,I,J)=99999!
330 NEXT:INPUT #1, O:NEXT:NEXT
340 REM
350 REM **** DAT(X) IS THE DESIRED ARRIVAL TIME IN *****
360 REM ************ SECONDS FROM MIDNIGHT *************
370 REM
380 CLS
390 FOR K=1 TO 10
400 P(K)=10
410 NEXT
420 REM DAT(1)=27600
421 DAT(1)=28800
430 REM
440 REM **** A,B,D ARE THE COST FUNCTION COEFFECIENTS *****
450 REM ****     T IS THE NUMBER OF TIME INTERVALS    *****
460 REM
470 A=6
480 B=3
490 D=1
500 REM
510 REM **** HERE THE START OF EACH TIME INTERVAL IS  *****
520 REM ****** CONVERTED TO SECONDS AFTER MIDNIGHT  *******
530 REM
540 TI(1)=7*3600
```

```
550 FOR I=2 TO (T-1)
560 TI(I)=TI(I-1)+10*60
570 NEXT
580 REM
590 REM ** THE DEMAND FILES ARE READ (VOLUME DEPARTING IN EACH TIME INTERVAL)

600 REM
610 OPEN "I",2,"c:DEMANDb"
620 FOR I=1 TO OD
622 FOR H=1 TO WST
630 INPUT #2, Q(1,I,H), Q(2,I,H), Q(3,I,H), Q(4,I,H), Q(5,I,H)
640 PRINT Q(1,I,H), Q(2,I,H), Q(3,I,H), Q(4,I,H), Q(5,I,H)
660 FOR J=1 TO (T-1)
670 INPUT #2, V(H,I,J)
680 PRINT V(H,I,J)
690 NEXT:NEXT:NEXT
700 CLOSE 2
710 REM
720 REM **** THIS LOOP (720-890) CALCULATES THE COST BASED ON THE SPEEDS ****
730 REM ******** WITH TRAVEL TIME CALCULATED ASSUMING DEPARTURE FROM ********
740 REM **************** THE MIDDLE OF EACH TIME INTERVAL ******************
750 REM
760 FOR I=1 TO OD
770 FOR H=1 TO WST
780 FOR J=1 TO (T-1)
790 REM **** LINE 420 DETERMINES IF VEHICLES DEPARTING IN A TIME ****
800 REM **** INTERVAL ARRIVED EARLY OR LATE, AND THEN ESTIMATES *****
810 REM ******** THE COST OF DEPARTING IN EACH TIME INTERVAL ********
820 REM
825 REM ***** 830 TO 860, EXAMPLE OF FLEXIBLE WORK START TIME *******
830 REM IF (TT(H,I,J)+TI(J)+(5*60)-DAT(H))>(10*60) THEN C(H,I,J)=TT(H,I,J)*A+
(H,I,J)+TI(J)+(5*60)-DAT(H)-10*60)*B
840 REM IF (TT(H,I,J)+TI(J)+(5*60)-DAT(H))<(-10*60) THEN C(H,I,J)=TT(H,I,J)*A
AT(H)-(10*60)-TT(H,I,J)-TI(J)-(5*60))*D
850 REM IF (TT(H,I,J)+TI(J)+(5*60)-DAT(H))<=(10*60) AND (TT(H,I,J)+TI(J)+(5*6
DAT(H))>=(-10*60) THEN C(H,I,J)=TT(H,I,J)*A
855 REM ***** 860 TO 880, EXAMPLE FOR RIGID DESIRED ARRIVAL TIME*****
860 IF (TT(H,I,J)+TI(J)+(5*60)-DAT(H))>0 THEN C(H,I,J)=TT(H,I,J)*A+(TT(H,I,J)
(J)+(5*60)-DAT(H))*B
870 IF (TT(H,I,J)+TI(J)+(5*60)-DAT(H))<0 THEN C(H,I,J)=TT(H,I,J)*A+(DAT(H)-TT
I,J)-TI(J)-(5*60))*D
880 IF (TT(H,I,J)+TI(J)+(5*60)-DAT(H))=0 THEN C(H,I,J)=TT(H,I,J)*A
885 PRINT C(H,I,J)
890 NEXT:NEXT:NEXT
900 GOSUB 1300
910 CLS
930 FOR I=1 TO OD
940 FOR H=1 TO WST
950 FOR J= 1 TO (T-1)
960 C$="#####"
970 PRINT USING C$;C(H,I,J),
980 NEXT
990 PRINT
1000 NEXT:NEXT
1010 PRINT
1020 REM
1030 REM **** LINES 1060 TO 1220 ARE EDITING THE DEMAND FILES FOR ***
1040 REM ***** INPUTTING INTO SUCCESSIVE ITERATIONS OF CONTRAM ****
```

```
1050 REM
1060 OPEN "o",2,"c:demandb"
1070 OPEN "o",3,"c:demand"
1080 E$=","
1090 PRINT #3, "CONTRAM - TEST NETWORK"
1100 FOR I=1 TO OD
1105 FOR H=1 TO WST
1110 PRINT #3, USING "#####"; Q(1,I,H),Q(2,I,H),Q(3,I,H),Q(4,I,H),Q(5,I,H),
1120 PRINT #2, USING "######"; Q(1,I,H),Q(2,I,H),Q(3,I,H),Q(4,I,H),Q(5,I,H),
1140 FOR J=1 TO (T-1)
1150 D$="#####"
1160 E$="######"
1170 IF J<(T-1) THEN PRINT #2, TAB(31+(J-1)*6) USING E$;V(H,I,J),
1180 IF J=(T-1) THEN PRINT #2, TAB(31+(J-1)*6) USING E$;V(H,I,J)
1190 IF J<(T-1) THEN PRINT #3, TAB(26+(J-1)*5) USING D$;V(H,I,J),
1200 IF J=(T-1) THEN PRINT #3, TAB(26+(J-1)*5) USING D$;V(H,I,J)
1210 NEXT
1220 NEXT:NEXT
1230 GOSUB 2030
1240 END
1250 REM
1260 REM *****   SUBROUTINE 1300 TO 1690 IS THE REASSIGNMENT *****
1270 REM ****  TECHNIQUE BY WHICH THE TEMPORAL DISTRIBUTIION ***
1280 REM ****    IS REDETERMINED FOR INPUT BACK TO CONTRAM  ****
1290 REM
1300 FOR I=1 TO OD
1305 FOR H=1 TO WST
1310 CMIN(I,H)=999999!
1320 FOR J=1 TO T-1
1330 ER(J)=0
1340 FOR K=1 TO T-1
1350 REM
1360 REM **** ER(J) IS THE SUM EXPECTED REDUCTION IN COST ****
1370 REM ********* IN SHIFTING DEPARTURE TIME FROM J *********
1380 REM
1390 IF C(H,I,J)>C(H,I,K) THEN ER(J)=ER(J) + (C(H,I,J)-C(H,I,K))
1400 NEXT
1410 REM
1420 REM **** ALL THE COSTS FOR EACH OD PAIR AND WORK START TIME ****
1430 REM **** ARE COMPARED IN ORDER TO DETERMINE THE MINIMUM COST ***
1440 REM
1450 IF C(H,I,J)<CMIN(I,H) THEN CMIN(I,H)=C(H,I,J)
1460 NEXT
1470 FOR J=1 TO T-1
1480 REM
1490 REM *** ALP(H,I,J) IS THE PERCENTAGE OF A TIME INTERVAL'S ***
1500 REM *************** VOLUME THAT GETS REASSIGNED **************
1505 PRINT C(H,I,J)
1510 REM
1520 ALP(H,I,J)=(C(H,I,J)-CMIN(I,H))/C(H,I,J)
1530 ALP(H,I,J)=ALP(H,I,J)^(1/2)
1540 REM **** IF ALP(H,I,J)>.05 THEN ALP(H,I,J)=ALP(H,I,J)^(1/2) ****
1550 V2(H,I,J)=V(H,I,J)*(1-ALP(H,I,J))
1560 NEXT
1570 REM
1580 REM **** LOOP 1600-1670 DETERMINES THE NEW VOLUME FOR EACH TIME INTERVAL

1590 REM
```

```
1600 FOR J=1 TO T-1
1610 FOR K=1 TO T-1
1620 IF ER(K)>0 AND C(H,I,K)>C(H,I,J) THEN V2(H,I,J)=V2(H,I,J)+V(H,I,K)*(ALP(
,K))*((C(H,I,K)-C(H,I,J))/ER(K))
1630 NEXT
1640 NEXT
1650 FOR J=1 TO T-1
1660 V(H,I,J)=V2(H,I,J)
1670 NEXT:NEXT:NEXT
1680 GOSUB 1760
1690 RETURN
1700 REM
1710 REM ****** THIS SUBROUTINE (WITHIN THE ABOVE SUBROUTINE ****
1720 REM **** ROUNDS OFF THE NEW VOLUMES IN EACH TIME INTERVAL***
1730 REM ****   THAT IS LESS THAN A PACKET SIZE TO 0 OR THE  ****
1740 REM **** PACKET SIZE, WHICHEVER IS CLOSER (LINES 1760-1940)**
1750 REM
1760 COUNT=0
1770 FOR I=1 TO OD
1775 FOR H=1 TO WST
1780 AD(I,H)=0:MIN(I,H)=0
1790 FOR J=1 TO T-1
1800 IF V(H,I,J)*10/60<P(I) THEN AD(I,H)=AD(I,H)+(P(I)/(10/60)-V(H,I,J))
1810 IF V(H,I,J)*10/60<P(I) THEN V(H,I,J)=P(I)/(10/60)
1820 NEXT
1830 IF AD(I,H)=0 THEN COUNT=COUNT+1
1840 IF AD(I,H)=0 THEN GOTO 1920
1850 TV=0
1860 FOR J=1 TO T-1
1870 IF V(H,I,J)*10/60>P(I) THEN TV=TV+V(H,I,J)
1880 NEXT
1890 FOR J=1 TO T-1
1900 IF V(H,I,J)*10/60>P(I) THEN V(H,I,J)=V(H,I,J)-(AD(I,H)*V(H,I,J)/TV)+(MIN
H)*V(H,I,J)/TV)
1910 NEXT
1920 NEXT:NEXT
1930 IF COUNT=OD THEN RETURN ELSE GOTO 1760
1940 RETURN
1950 REM
1960 REM *** THIS FINAL SUBROUTINE EDITS THE BATCH ***
1970 REM *** FILE AND RELATED FILES THAT COPY THE ****
1980 REM ** OUPUT FROM CONTRAM AND THIS PROGRAM SO ***
1990 REM ** THAT THE SUCCESSIVE ITERATIONS WILL NOT***
2000 REM **** OVER WRITE IT.  IT ALSO CHECKS THE  ****
2010 REM *** NUMBER OF ITERATIONS.               *****
2020 REM
2030 CLOSE 2,3
2040 OPEN "I",3,"ITER"
2050 INPUT #3, ITER
2060 CLOSE #3
2070 IF ITER<22 THEN OPEN "O",3,"DUP.BAT" ELSE GOTO 2200
2080 IF ITER <10 THEN PRINT #3, "COPY B:RESULTS c:rvol";:PRINT #3, USING "#";
R
2090 IF ITER <10 THEN PRINT #3, "COPY c:cost c:rvcos";:PRINT #3, USING "#";IT
2095 IF ITER <10 THEN PRINT #3, "COPY c:demand c:rvdem";:PRINT #3, USING "#";
R
2100 IF ITER >9 THEN PRINT #3, "COPY B:RESULTS c:rvol";:PRINT #3, USING "##";
R
```

```
2110 IF ITER >9 THEN PRINT #3, "COPY c:cost c:rvcos";:PRINT #3, USING "##";IT
2115 IF ITER >9 THEN PRINT #3, "COPY c:demand c:rvdem";:PRINT #3, USING "##";
R
2120 PRINT #3, "if exist last goto nnnn"
2130 PRINT #3,"CONTRAM"
2140 PRINT #3, ":nnnn"
2150 ITER=ITER+1
2160 CLOSE #3
2170 OPEN "O",3,"ITER"
2180 PRINT #3, ITER
2190 CLOSE 3
2200 IF ITER=22 THEN OPEN "O",3,"c:LAST"
2210 OPEN "o",2,"c:cost"
2220 FOR I=1 TO OD
2230 FOR H=1 TO WST
2240 FOR J=1 TO T
2250 PRINT #2, C(H,I,J)
2260 NEXT:NEXT:NEXT
2270 RETURN
```